Robotic System Architecture

High Level Introduction

Robotic System – Definitions

Robotic System – Definition – Merrian Webster

Robot (noun)

ro·bot | \ ˈrō-ˌbät , -bət \

plural **robots**

Definition of *robot*

1: a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)

Often **:** such a machine built to resemble a human being or animal in appearance and behavior.

2a: a device that automatically performs complicated, often repetitive tasks (as in an industrial assembly line)

b: a mechanism guided by automatic controls

Did you Know?

In 1920, Czech writer Karel Čapek published a play titled R.U.R. Those initials stood for "Rossum's Universal Robots," which was the name of a fictional company that manufactured human-like machines designed to perform hard, dull, dangerous work for people. The machines in the play eventually grew to resent their jobs and rebelled—with disastrous results for humans. During the writing of his play, Čapek consulted with his brother, the painter and writer Josef Čapek, who suggested the name robot for these machines, from the Czech word robota, which means "forced labor." Robot made its way into our language in 1922 when R.U.R. was translated into English.

Robotic System – Definition – Britanica

Robot (noun)

ro·bot | \ ˈrō-ˌbät , -bət \

plural **robots**

Definition of *robot*

1: a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)

Often **:** such a machine built to resemble a human being or animal in appearance and behavior.

2a: a device that automatically performs complicated, often repetitive tasks (as in an industrial assembly line)

b: a mechanism guided by automatic controls

Robotic System – Definition – IEEE

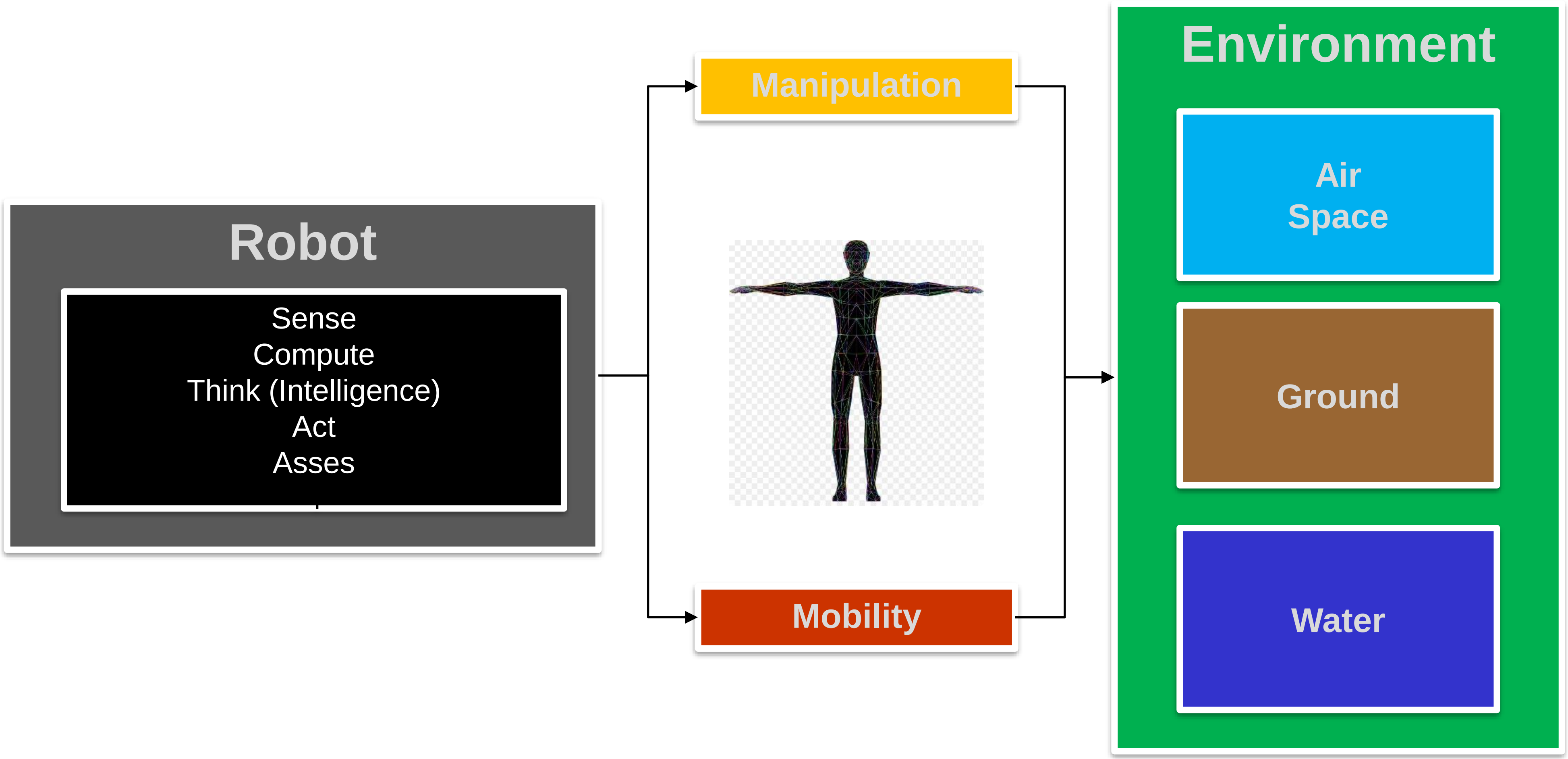
https://robots.ieee.org/learn/what-is-a-robot/

Rodney Brooks
Professor of Robotics Emeritus at MIT, Co-founder and CTO of Robust AI

Three characteristics of a robotic system

1. Sense
2. Compute
3. Act

Robotic System – Definition



Fundamental Problems in Robotics Manipulation

Task Description

Description of Positioning Task

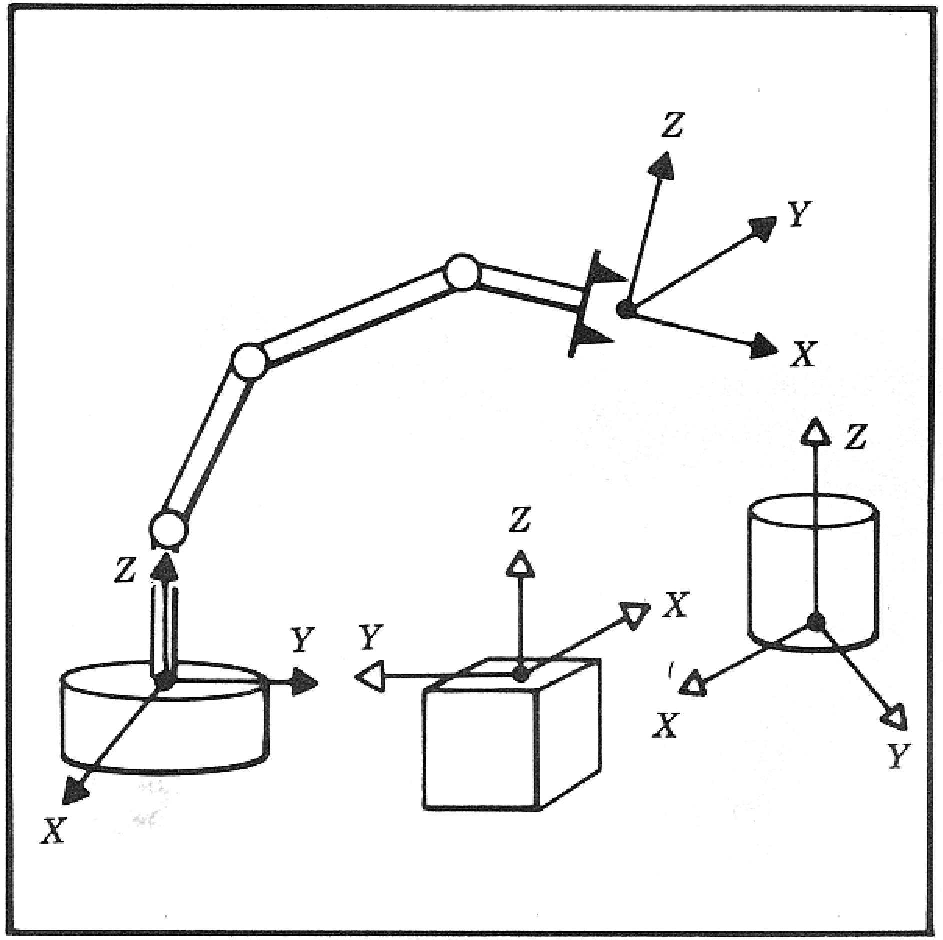
Problem

Given: *The manipulator geometrical parameters*

Specify: *The position and orientation of manipulator*

Solution

Coordinate system or "Frames" are attached to the manipulator (using the DH convention) and objects in the environment



Kinematics

Forward, Inverse, Jacobian (Velocity, Force)

Forward (Direct) Kinematics (FK)

Problem

Given: *Joint angles and links geometry*

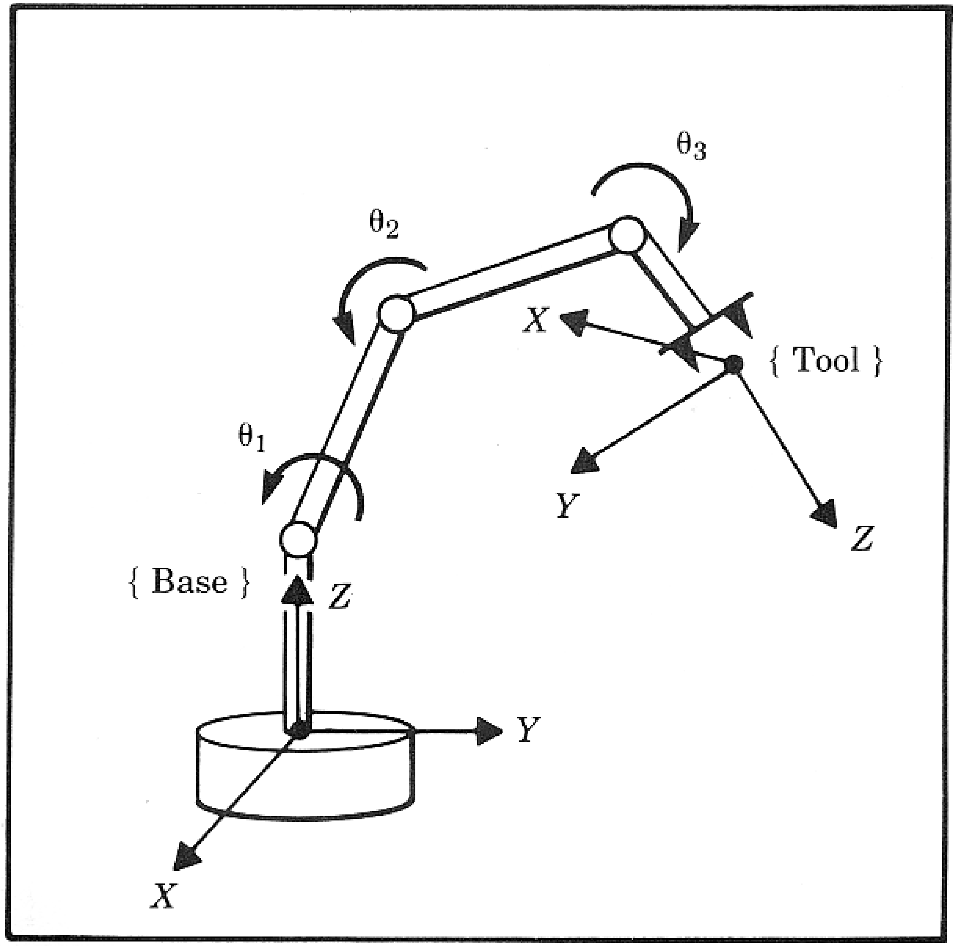
Compute: *Position and orientation of the end effector relative to the base frame*

Solution

Kinematic Equations - Linear Transformation (4x4 matrix) which is a function of the joint positions (angles & displacements) and specifies the EE configuration in the base frame.

Note

- **Mapping First to Last Joint** - The FK address the pose of every joint with respect the base frame (Frame 0) and in particular the pose of the last frame of the manipulator (e.g. frame 6 for a 6 DOF manipulator)
- **Mapping Last Joint to Tool Tip** - The mapping between the tool tip and the last frame is known by definition. This mapping may change based on the tool being used therefore it is not included in the FK analysis that focused on the core of the robotic arm (e.g. the first 6 joint of the robotic arm)
- **Where is the Tool** -The FK kinematics in general including the mapping of the tool tip with respect to the last joint answers the question of **where is the tool**



Inverse Kinematics

Problem

Given: *Position and orientation of the end effector relative to the base frame*

Compute: *All possible sets of joint angles and links geometry which could be used to attain the given position and orientation of the end effetor.*

Solution

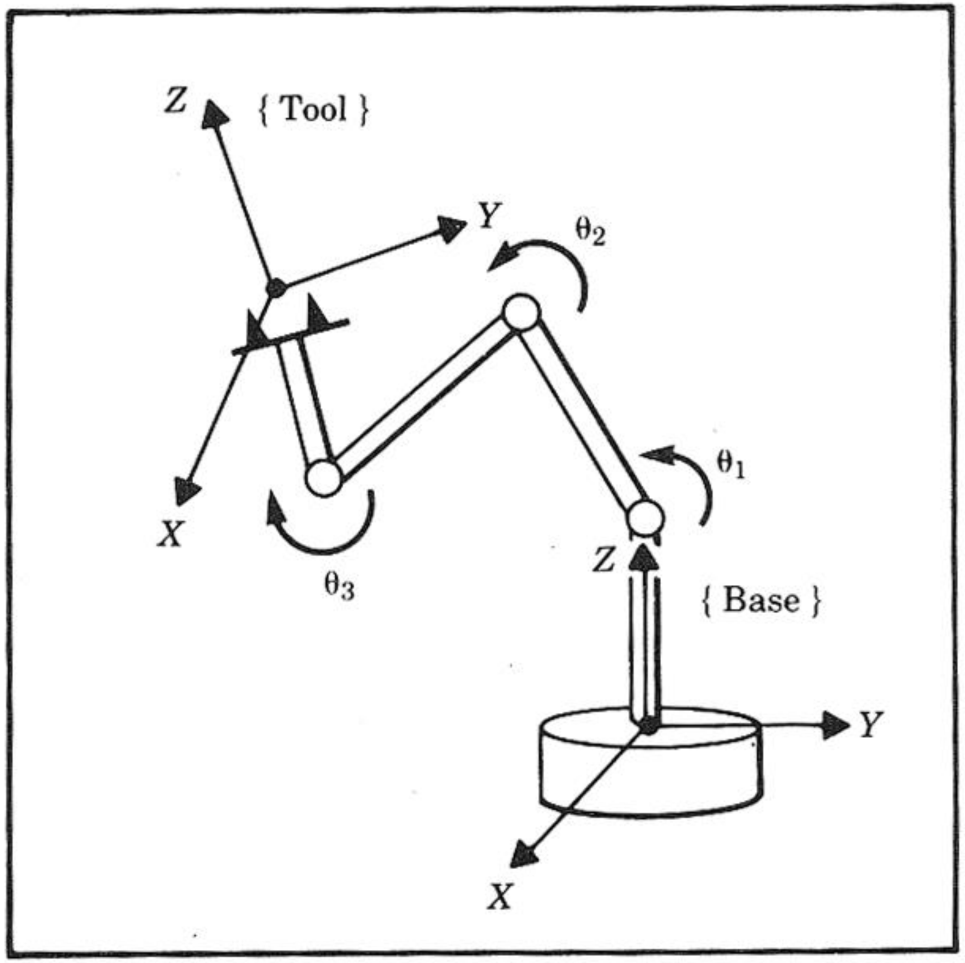
Does a close form solution exist?

Close Form Solutions - There are three approaches for the solution:

- **Analytical Approach** - Kinematic Equations - Linear Transformation (4x4 matrix) which is a function of the joint positions (angles & displacements) and specifies the EE configuration in the base frame. This linear transformation defines 12 non linear equations A subset of these equations are used for obtaining the invers kinematics
- **Geometric Approach** – Projecting the arm configurations on specific planes and using geometrical consideration to obtain the invers kinematics
- **Hybrid Approach** - Synthesizing the analytical and the geometrical approaches

Non Close Form Solution

- Numerical Solution



Velocity Transformation

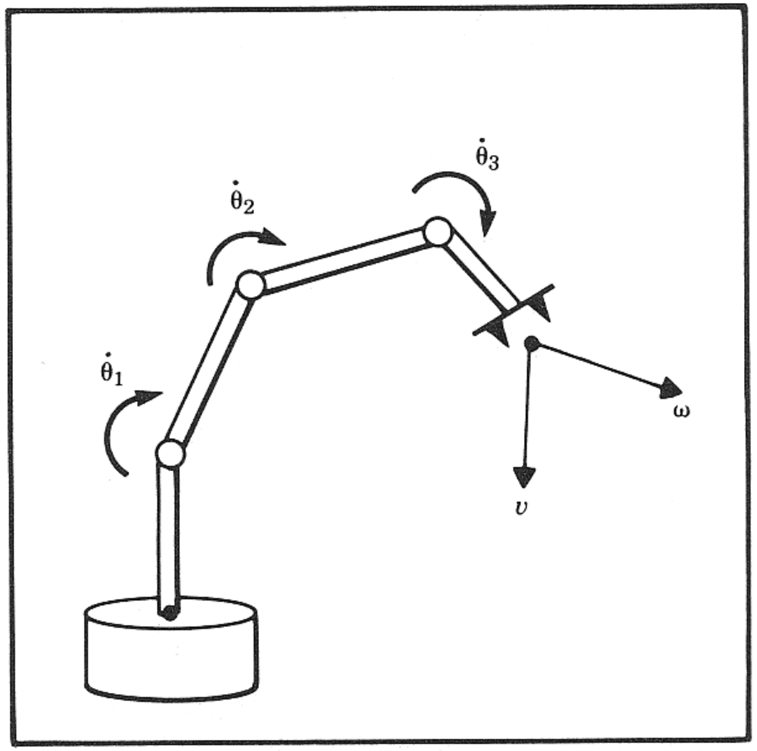
Problem

Given: Joint angles and velocities and links geometry along with the transformation matrixes between the joints.

Compute: The Jacobian matrix that maps between the joint velocities $\dot{\Theta}$ in the joint space to the end effector velocities ν in the Cartesian space or the end effector space

$$\nu = \mathbf{J}\,(\Theta)\dot{\Theta}$$

$$\dot{\Theta} = \mathbf{J}^{-1}(\Theta)\nu$$



$$\dot{\Theta} = \begin{Bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ d_4 \\ \dot{\theta}_5 \\ \dot{\theta}_6 \end{Bmatrix}$$

$$\nu = \begin{Bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix}$$

Solution – There are two approaches to the solution:

- **Velocity Propagation** - A velocity propagation approach is taken in which velocities are propagated stating form the stationary base all the way to the end effector. The Jacobian is then extracted from the velocities of the end effector as a function of the joint velocities.
- **Time derivative of the end effector position and ordinations** – The time derivative of the explicit positional and orientation is taken given the forward kinematics. The Jacobian is then extracted from the velocities of the end effector as a function of the joint velocities.

Notes:

Spatial Description – The matrix is a function of the joint angle.

Singularities - At certain points, called ***singularities***, this mapping is not invert-able and the Jacobian Matrix J loosing its rank and therefore this mathematical expression is no longer valid.

Force Transformation

Problem

Given: *Joint angles, links geometry, transformation matrixes between the joints, along with the external loads (forces and moments) typically applied on the end effector*

Compute: *The transpose Jacobian matrix that maps between the external loads (forces and moments) typically applied at the end effector space*$\mathcal{F}$ joint torques at the *joint space* $\boldsymbol{\tau}$

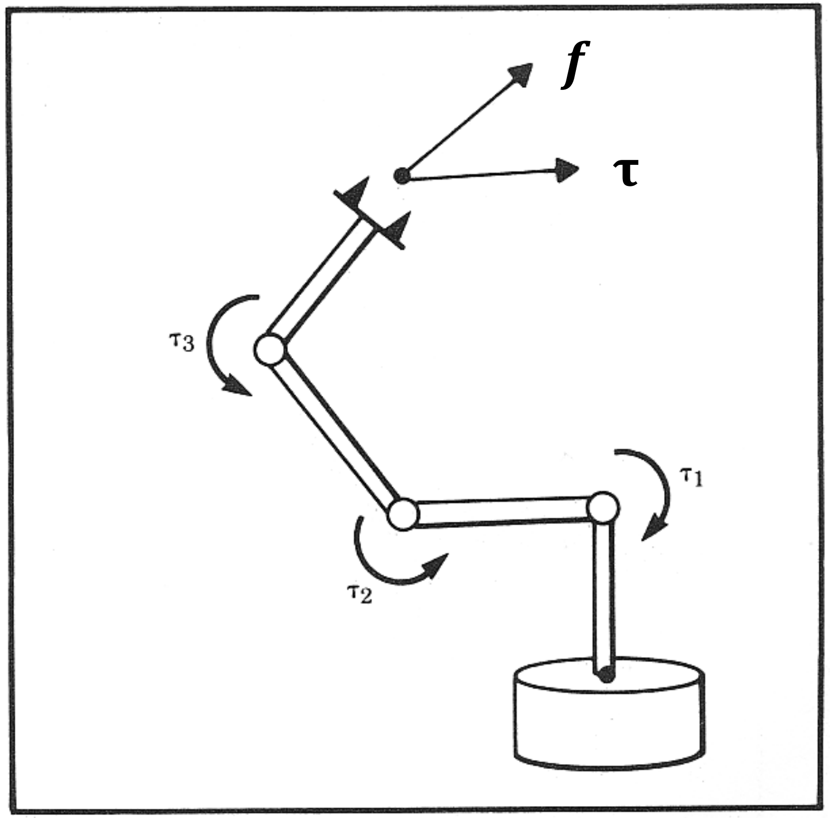
$$\tau = \mathbf{J}^T \mathcal{F}$$

Solution

- **Force/Moment Propagation** - A force/moment propagation approach is taken in which forces and moments are propagated stating form the end effector where they can be measured by a F/T sensor attached between the gripper and the arm all the way to the base of the arm. The Jacobian transposed is then extracted from the joint torques as a function of the force/moment applied on the end effector

Note

- **Conditions:** Static or quasi static conditions



$$\dot{\Theta} = \begin{Bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ f_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix}$$

$$\mathcal{F} = \begin{Bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \\ \tau_z \end{Bmatrix}$$

Dynamics

Forward Dynamics

Problem

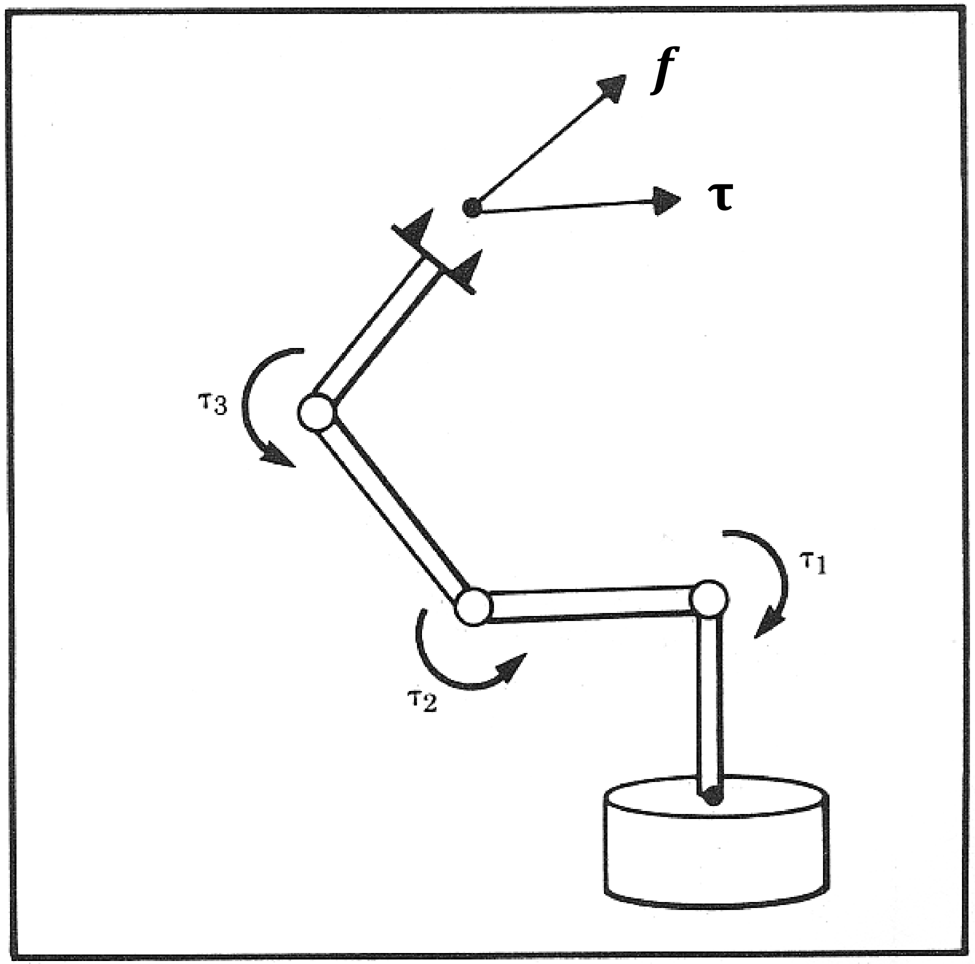
Given: Joint torques and links geometry, mass, inertia, friction

*Compute: Angular acceleration of the links **(i.e. Solve Differential Equations)***

Solution

Dynamic Equations - Newton-Euler method or Lagrangian Dynamics

$$\boldsymbol{\tau} = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) + \boldsymbol{\mathcal{F}}(\Theta,\dot{\Theta})$$



Inverse Dynamics

Problem

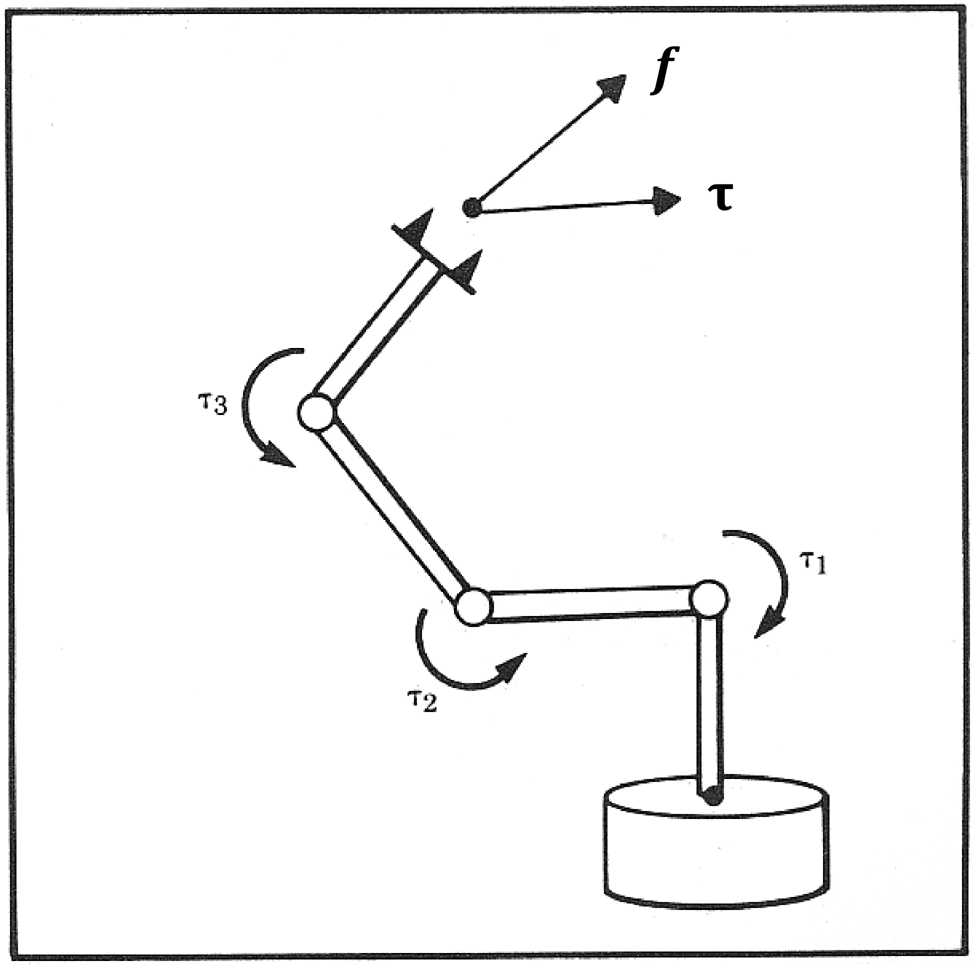
Given: *Angular acceleration, velocity and angels of the links in addition to the links geometry, mass, inertia, friction*

Compute: *Joint torques* ***(i.e. Solve Algebraic Equation)***

Solution

Dynamic Equations - Newton-Euler method or Lagrangian Dynamics

$$\boldsymbol{\tau} = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) + \mathcal{F}(\Theta,\dot{\Theta})$$



Trajectory

Join Space, Task (End Effector) Space

Trajectory Generation

Problem

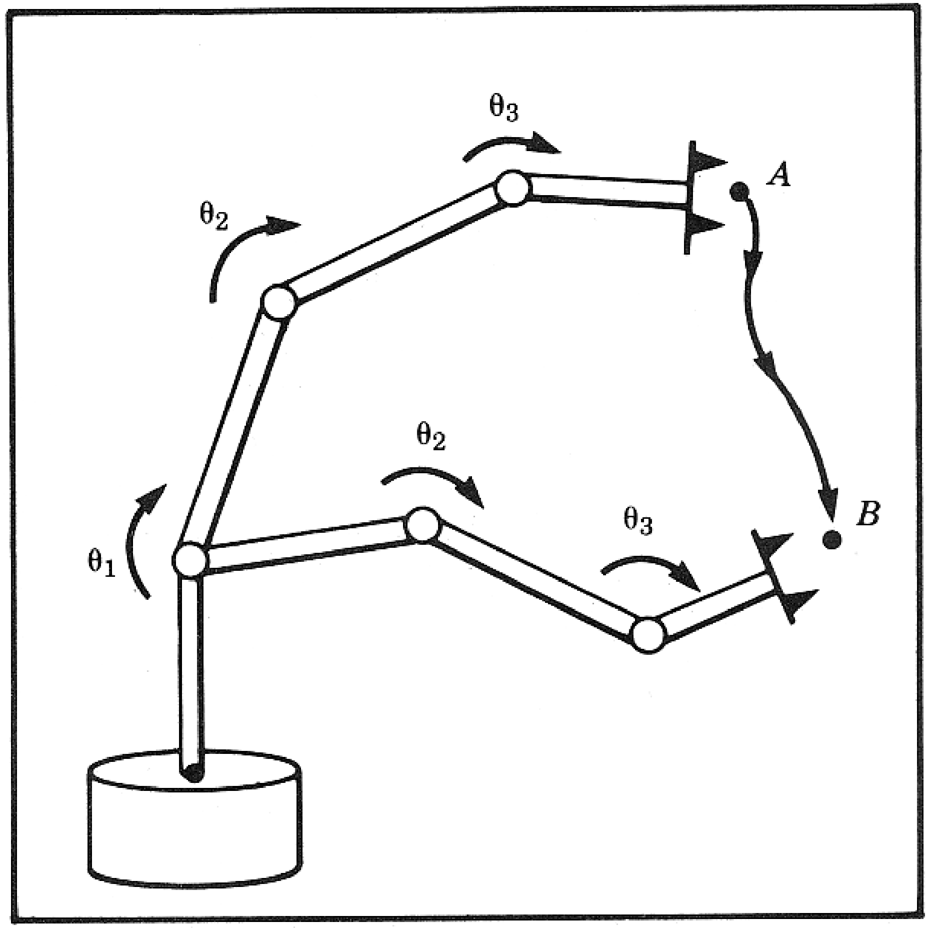
Given: Manipulator geometry

Compute: The trajectory of each joint such that the end efferctor move in space from point A to Point B

Solution

Third order (or higher) polynomial, spline.
Interpolation in either:

- Task / End Effector Space
- Joint Space



Control

Position, Force, Hybrid, Impedance, Teleoperation

Position Control

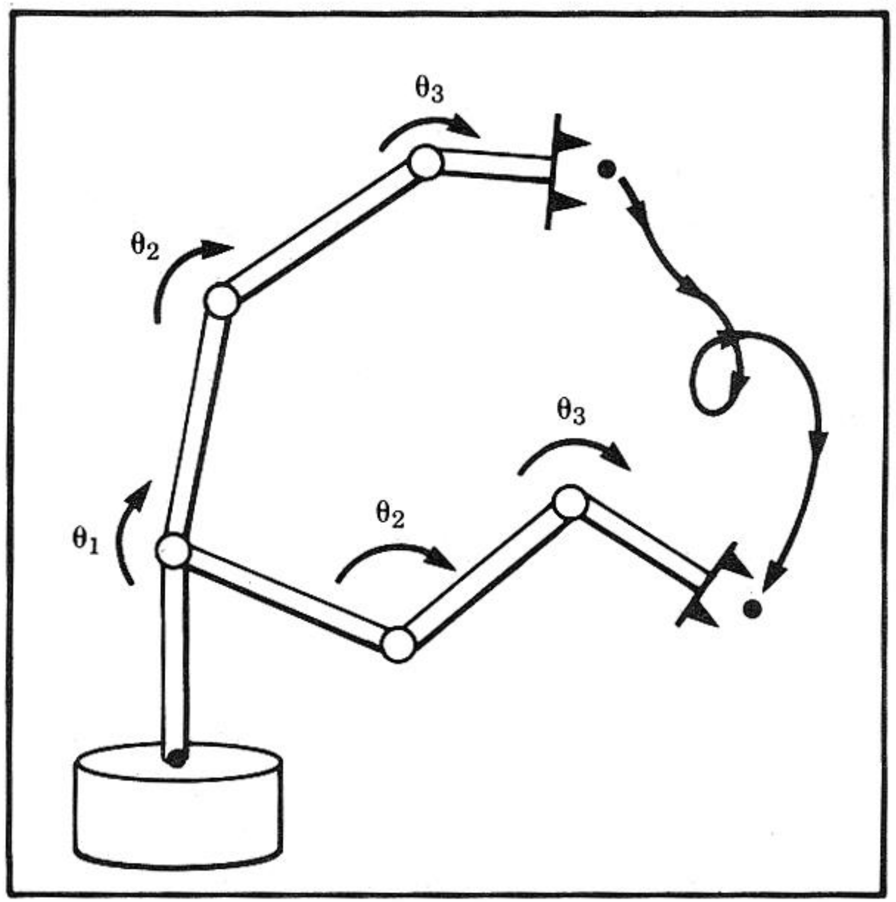
Problem

Given: Joint angles (*sensor readings) links geometry, mass, inertia, friction*

Compute: Joint torques to achieve an end effector trajectory

Solution

Control Algorithm (PID - Feedback loop, Feed forward dynamic control)



Force Control

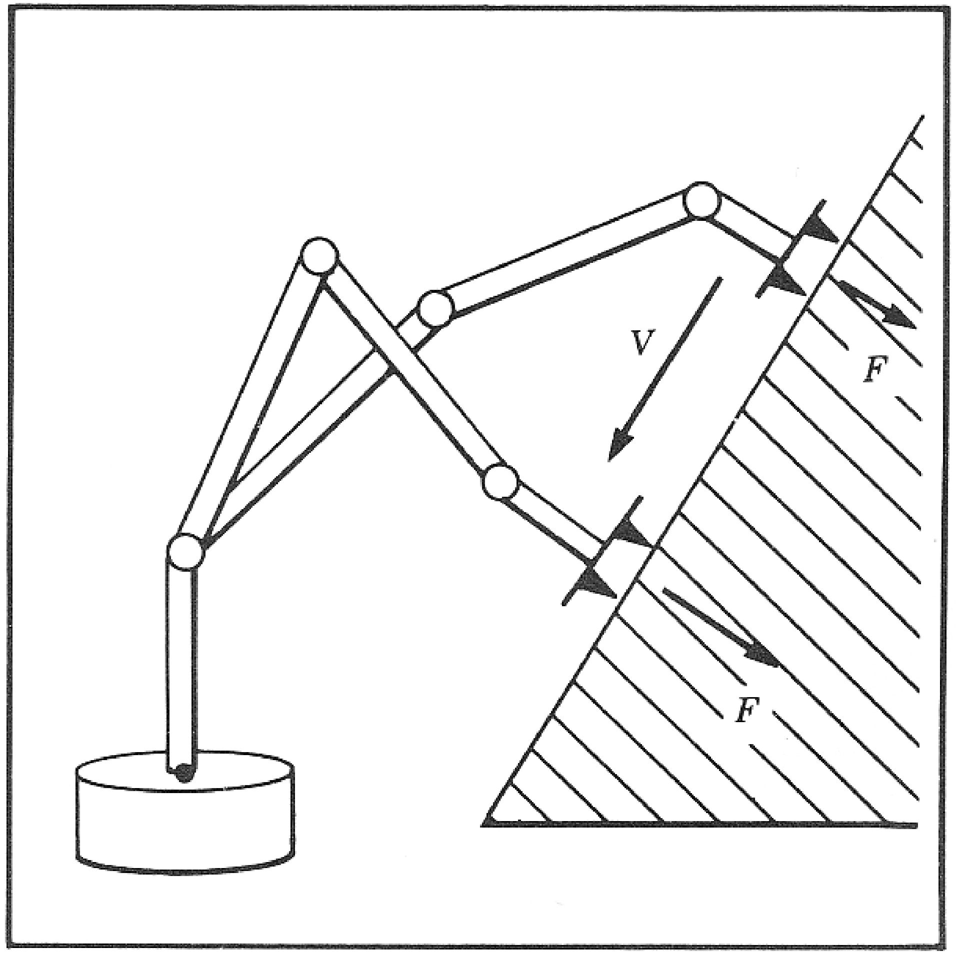
Problem

Given: Joint torque or end effector Force/torque interaction (sensor readings) links geometry, mass, inertia, friction

Compute: Joint torques to achieve an end effector forces an torques

Solution

Control Algorithm (force control)



Hybrid Control

Problem

Scraping paint from a surface

Solution

Control type: Hybrid Control

Note: It is possible to control position (velocity) **OR** force (torque), but not both of them simultaneously along a given DOF. The environment impedance enforces a relationship between the two

Assumption:

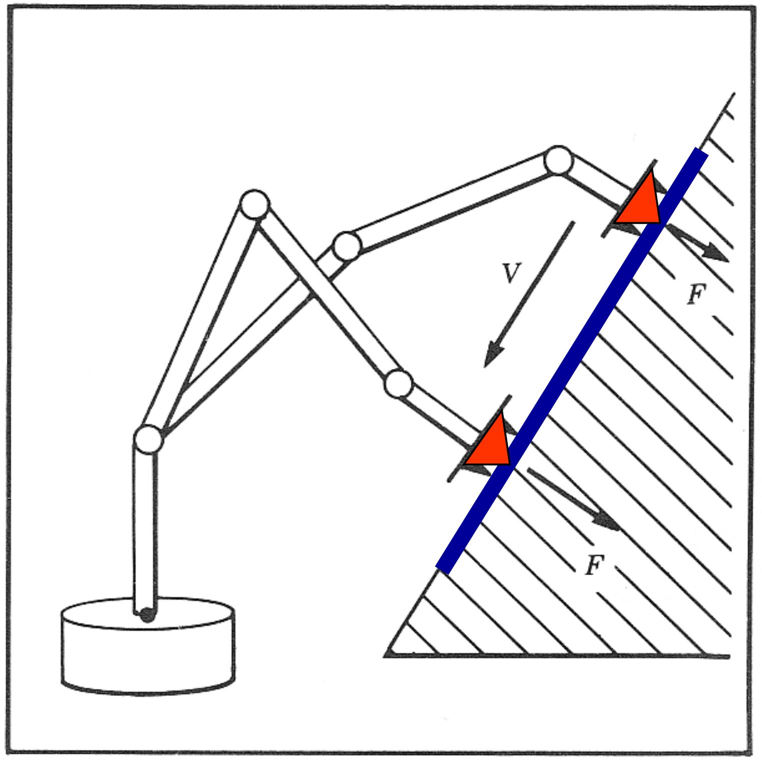
(1) The tool is stiff

(2) The position and orientation of the window is NOT known with accurately respect to the robot base.

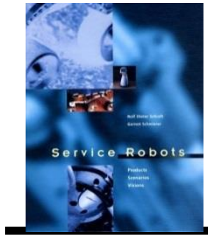
(3) A contact force normal to the surface transmitted between the end effector and the surface is defined

(4) Position control - tangent to the surface

(5) Force control – normal to the surface



Universal Robots "Force Control Surface Grinding"



Hybrid Control - Robotic Systems - Cleaning

SKYWASH

AEG, Dornier, Fraunhofer Institute, Putzmeister - Germany

Using 2 Skywash robots for cleaning a Boeing 747-400 jumbo jet, its grounding time is reduced from 9 to 3.5 hours. The world´s largest cleaning brush travels a distance of approximately 3.8 kilometers and covers a surface of around 2,400 m² which is about 85% of the entire plane´s surface area.

The kinematics consist of ***5 main joints*** for the robot´s arm, and an additional ***one for the turning circle*** of the rotating washing brush.The Skywash includes ***database that contains the aircraft-specific geometrical data***.

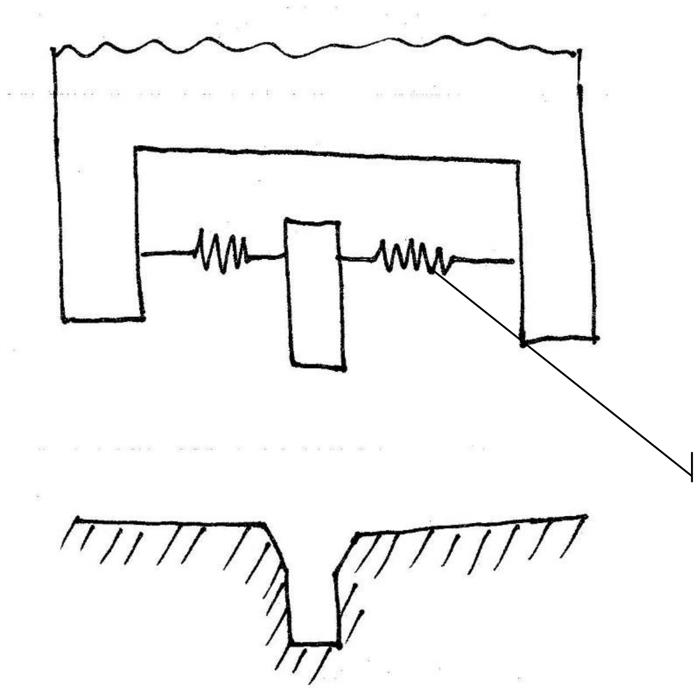
A ***3-D distance camera*** accurately positions the mobile robot next to the aircraft. The 3-D camera and the computer determine the aircraft´s ideal positioning, and thus the cleaning process begins.

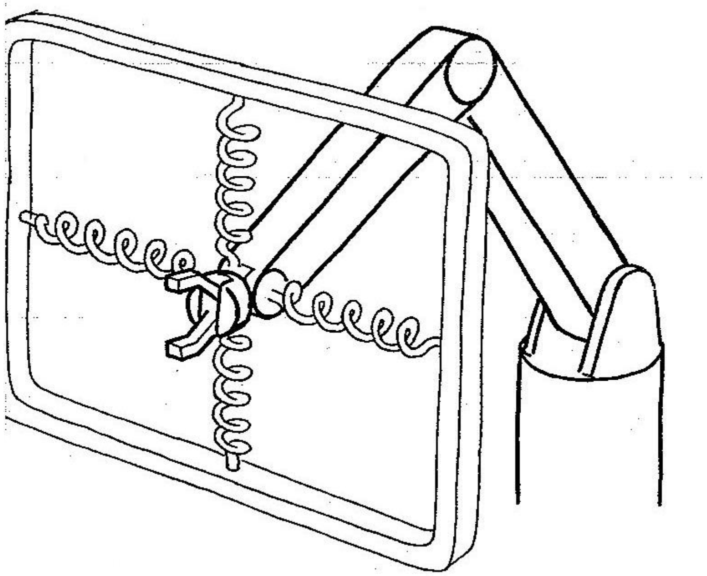

REDUCED USAGE OF WATER AND DETERGENT UP TO 40%

Impedance Control

- Controlling a DOF in strict position or force control represent control at two ends of the servo stiffness
  - **Ideal position servo** is infinitely stiff $K = dF/dX = \infty$ and reject all force disturbance acting on the system
  - **Ideal force servo** exhibits zero stiffness $K = dF/dX = 0$ and maintain a desired force application regardless of the position disturbance.

Controlling variable		Stiffness
Position (P)	$P_d - P = 0$	$K = dF/dX = \infty$
Force (F)	$F_d - F = 0$	$K = dF/dX = 0$


Virtual Springs



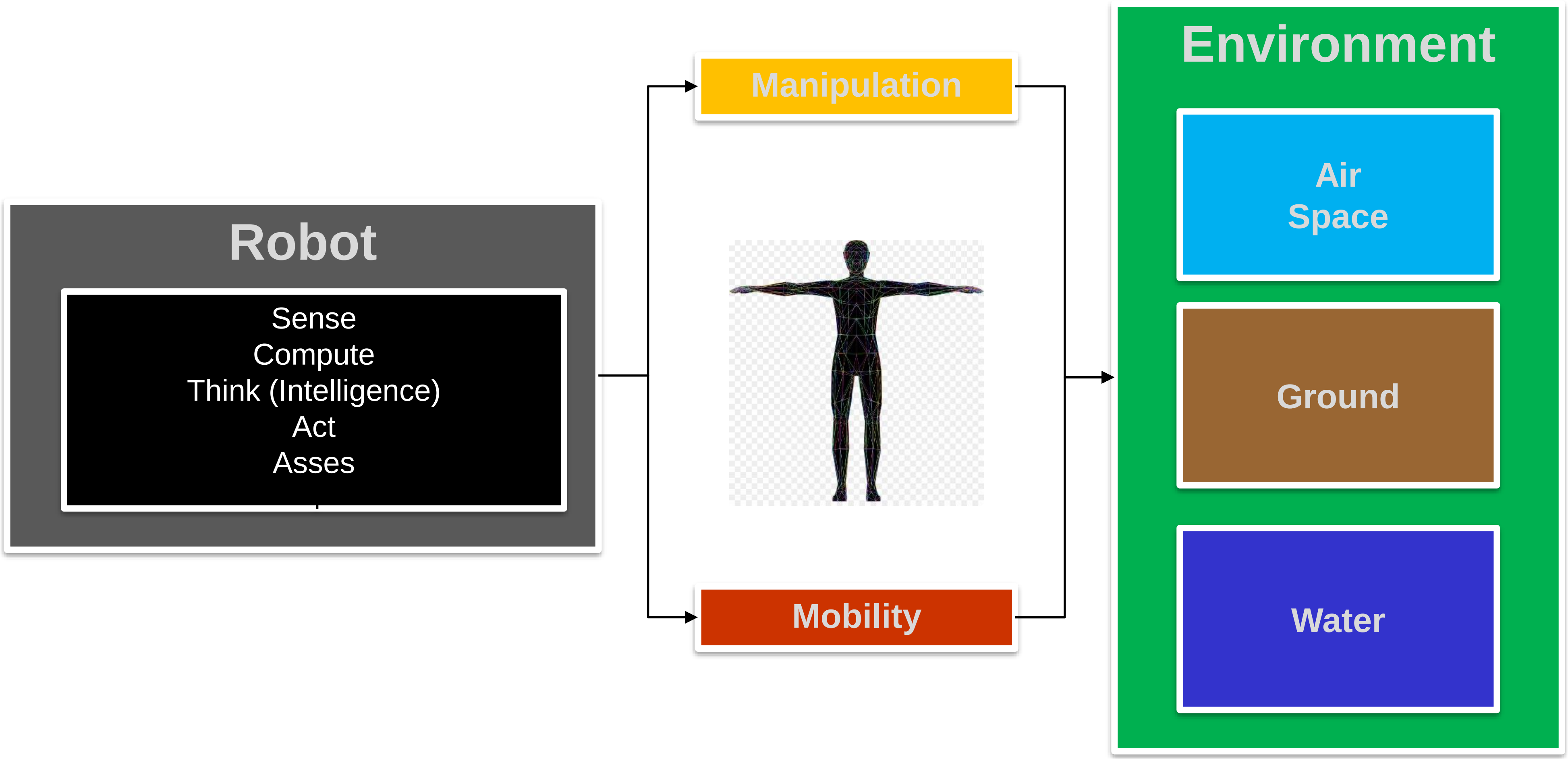

ESn Control
Cartesian
DLR
-55N

The Operational Environment

Structured versus Unstructured Environment

Static versus Dynamic Environment

Robotic System – Definition



Structured versus Unstructured Environment – Definition

Structured Environment

In the context of robotics, a structured environment refers to:

- Clearly defined boundaries
- Known object placement
- Consistent lighting and conditions
- Regular and structured features
- Reduced uncertainty

A controlled and predefined setting designed to facilitate the operation and movement of robots. It typically involves an environment that is organized, predictable, and well-defined, providing clear constraints and guidelines for robotic systems to navigate and interact with their surroundings.

Unstructured Environment

In the context of robotics, an unstructured environment refers to:

- Lack of defined boundaries
- Variability in object placement
- Changing conditions
- Complex features and clutter
- Uncertain or unknown elements

A setting that lacks clearly defined boundaries, predictable conditions, and consistent features. It is characterized by the presence of uncertainties, variations, and complex interactions with the surroundings. In an unstructured environment, robots encounter diverse and changing situations that require adaptability, robustness, and the ability to handle ambiguity.

Static versus Dynamic Environment – Definition

Static Environment

A static environment refers to a setting where the surrounding conditions and objects remain relatively fixed and unchanging during the robot's operation. It implies that the environment does not undergo significant variations or movements that could affect the robot's perception, planning, or execution of tasks. Key characteristics of a static environment in robotics include:

- Stationary objects
- Predictable conditions
- Known obstacles and boundaries
- Absence of time dependent events

Operating in a static environment can simplify the robot's perception, planning, and control processes, as it allows for more deterministic and pre-determined behaviors.

Dynamic Environment

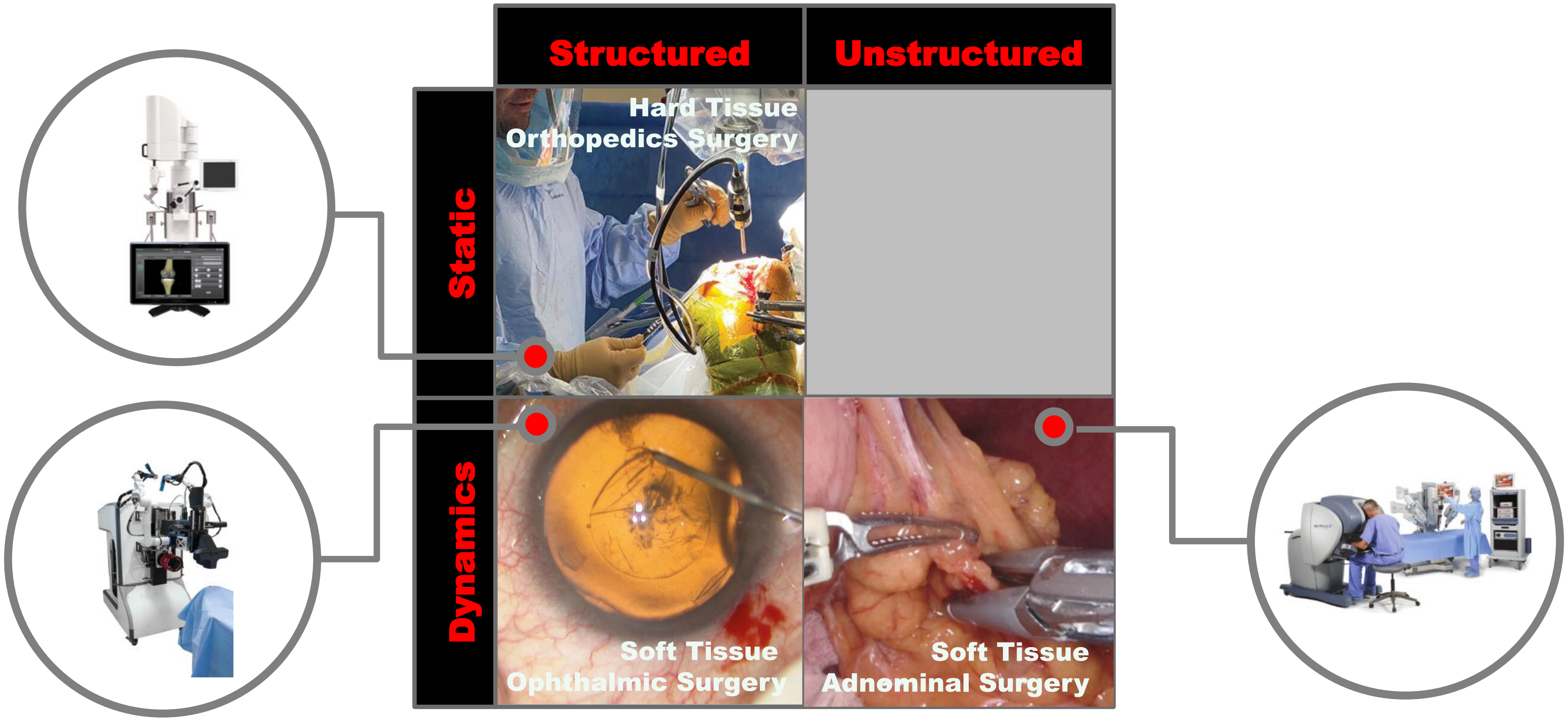
In the context of robotics, an unstructured environment refers to:

- Lack of defined boundaries
- Variability in object placement
- Changing conditions
- Complex features and clutter
- Uncertain or unknown elements

A setting that lacks clearly defined boundaries, predictable conditions, and consistent features. It is characterized by the presence of uncertainties, variations, and complex interactions with the surroundings. In an unstructured environment, robots encounter diverse and changing situations that require adaptability, robustness, and the ability to handle ambiguity.

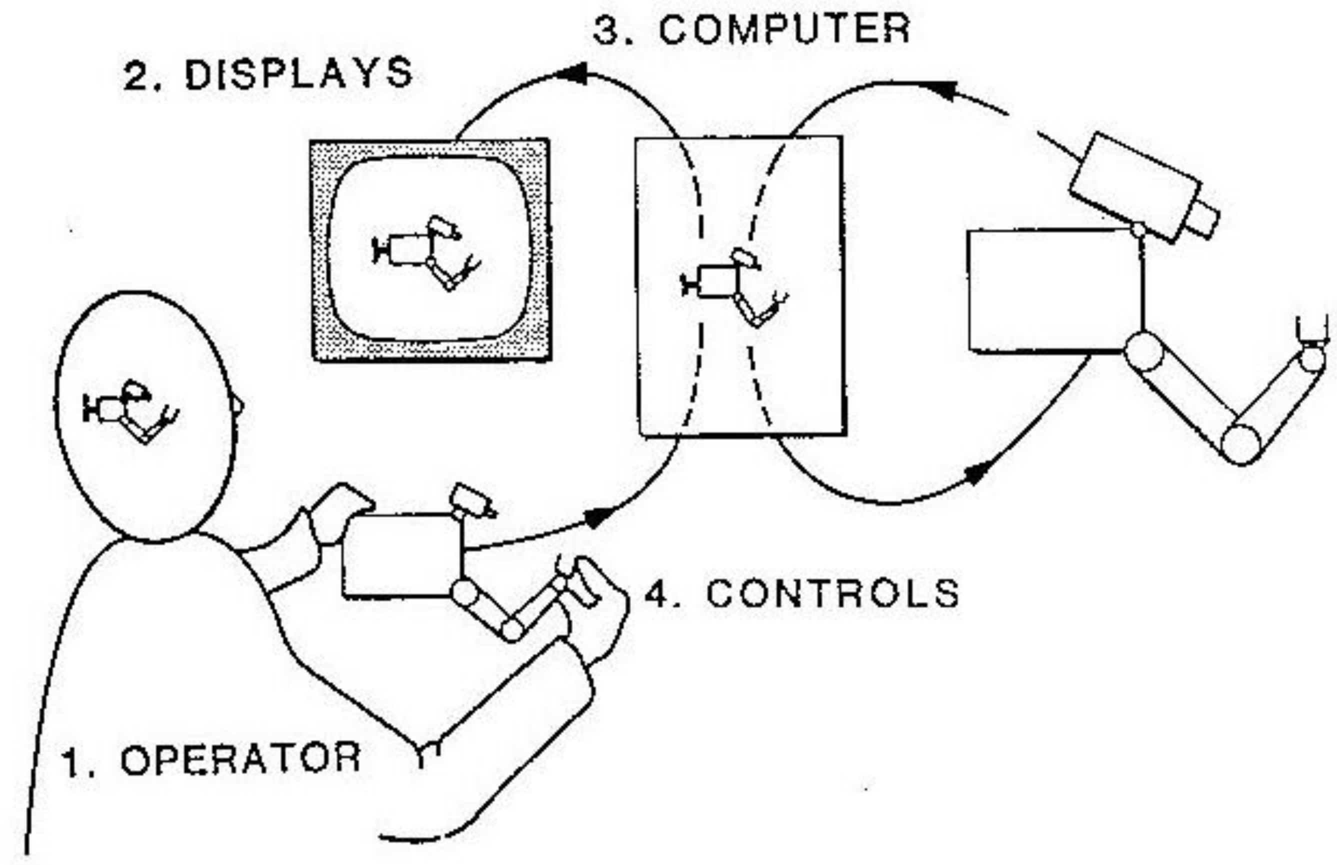
Automated Car Assembly Line

Surgical Robotics Environment

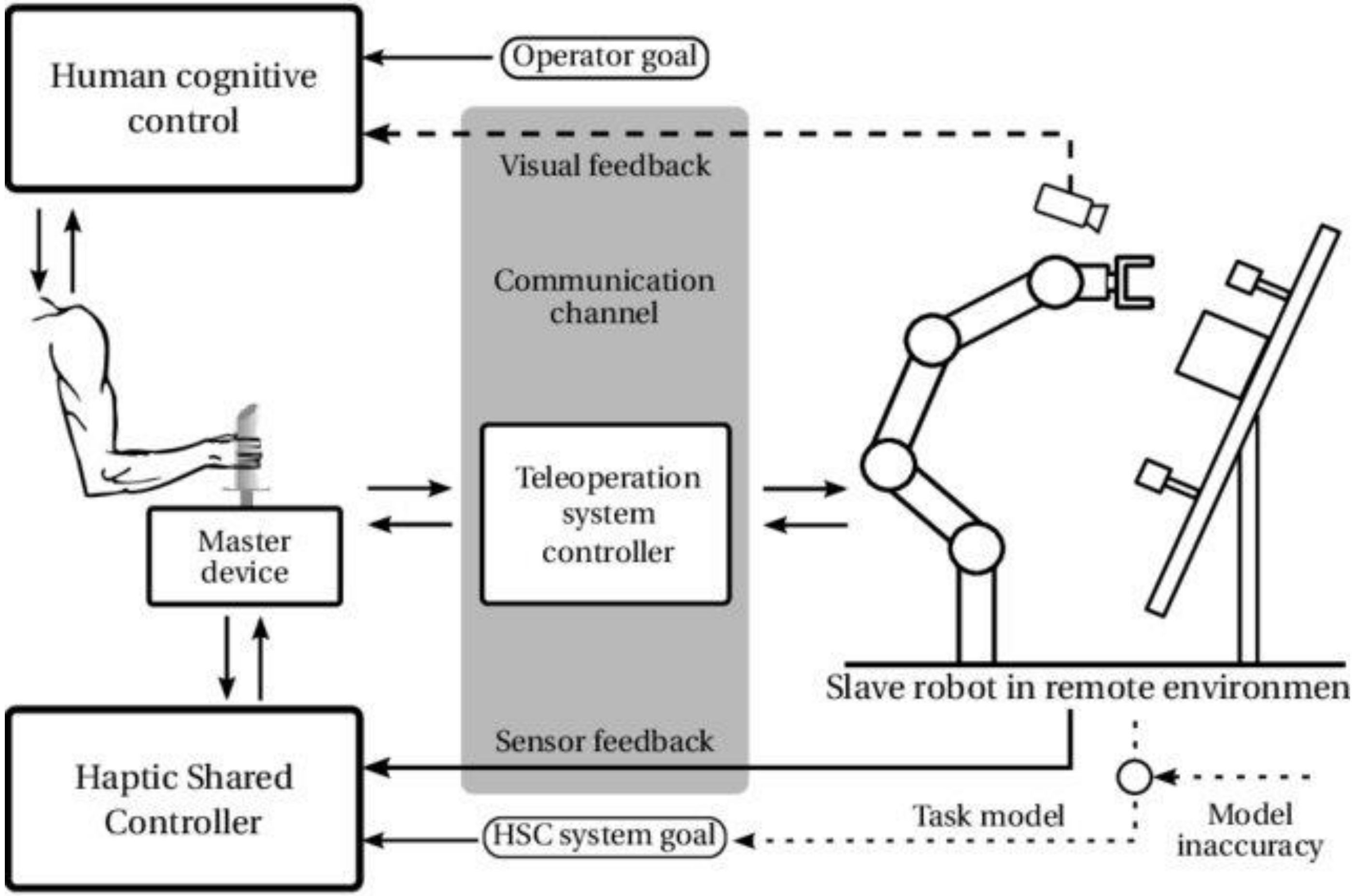


The Modes of Operation

Teleoperation



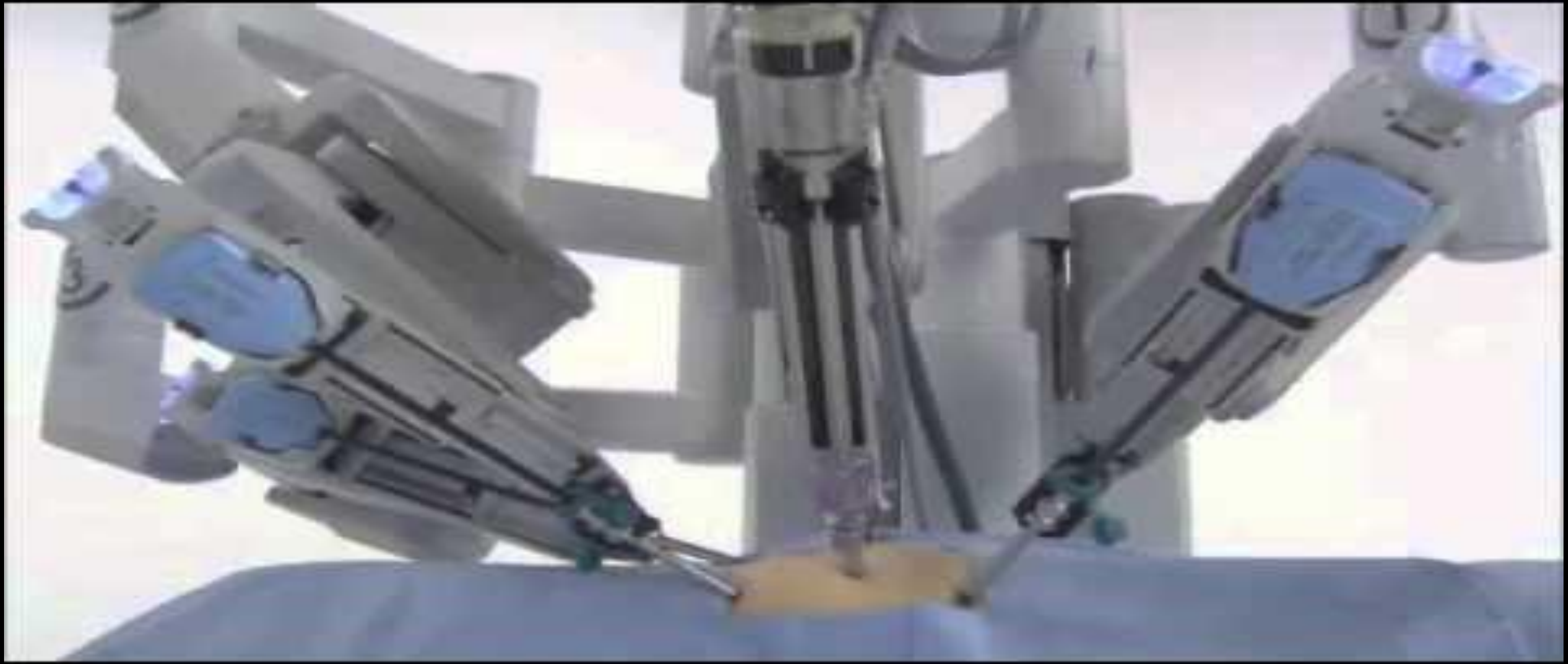
Teleoperation



Surgical robot teleoperation with BBZ console

Teleoperation

Video Hyperlink



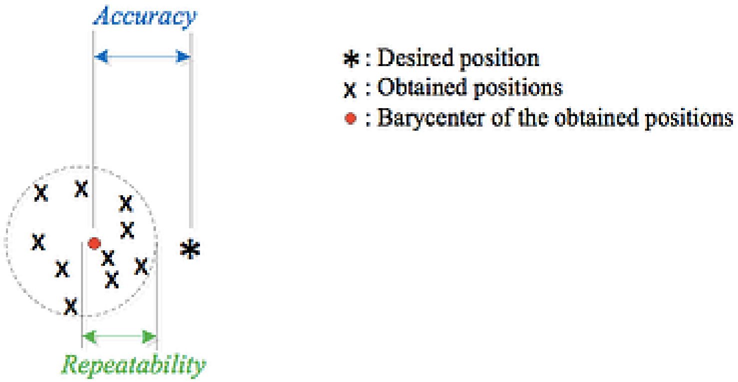
da Vinci® Surgery - How It Works

Accuracy Precision

Accuracy / Precision

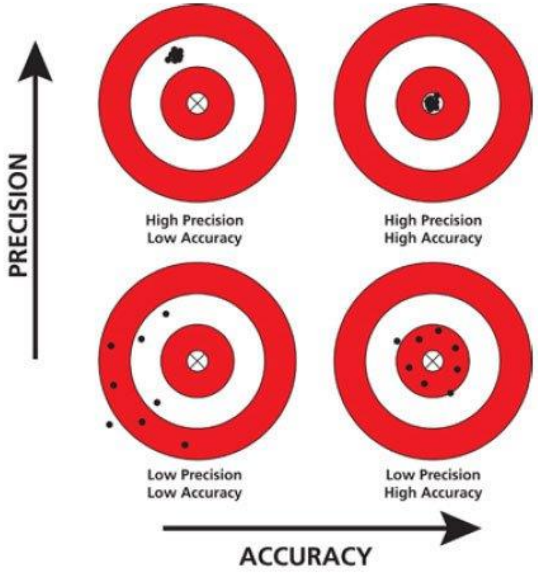
Accuracy (Definition)

Geometrically, the position accuracy of the robot for a given position can be defined as being the distance between the desired position and the centroid position (centroid is the mean position of all the points in all of the coordinate directions) which is actually achieved after repetitive movements of the end-effector toward the original desired position (see the Figure below). Mathematically, absolute accuracy is the compilation of the composed errors for each of the x, y, z cartesian positional errors. Finally, the robot position accuracy for a specific workspace can be described as the maximum composed error available for several positions uniformly distributed inside the predetermined workspace or reference frame.



Precision / Repeatability (Definition)

Repeatability can be defined as the closeness of agreement between several positions reached by the robot's end-effector for the same controlled position, repeated several times under the same conditions. Geometrically, the position repeatability can be defined as the radius of the smallest sphere that encompasses all the positions reached for the same requested position. For more details about the calculation of accuracy and repeatability, interested readers are referred to the ISO: International Organization for Standardization. 1998. Manipulating industrial robots – Performance criteria and related test methods, NF EN ISO9283.



https://youtu.be/9orN_aUDY7w

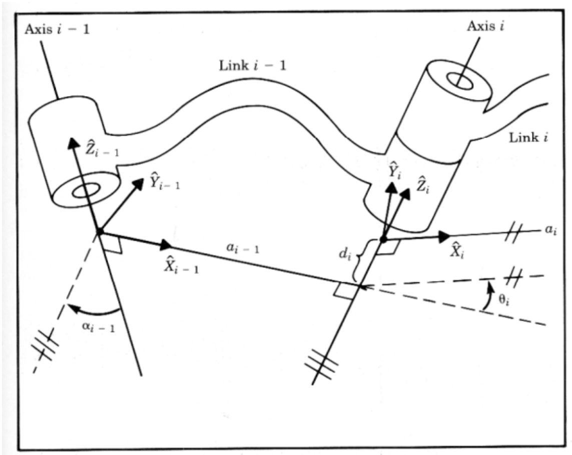
Calibration Registration

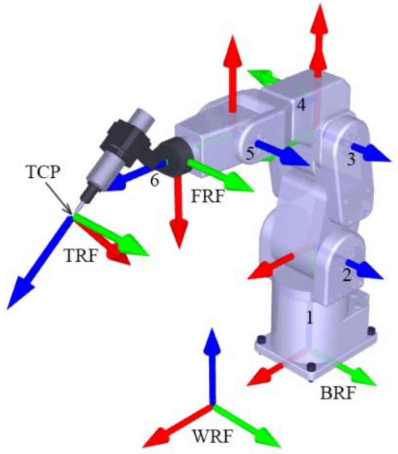
Calibration

- **Calibration –** The process used for improve the accuracy of robots. Depending on the type of errors modeled, the calibration can be classified in three different ways.

  - **Level-1 calibration** - Models differences between actual and reported joint displacement values, (also known as mastering).
  - **Level-2 calibration (kinematic calibration)** Models the entire geometry of the robot including: angle offsets, axis offset, axis twist, joint lengths.
  - **Level-3 calibration (non-kinematic calibration)**, models errors other than geometric defaults such as stiffness, joint compliance, and friction.

  - Note - Often Level-1 and Level-2 calibrations are sufficient for most practical needs.



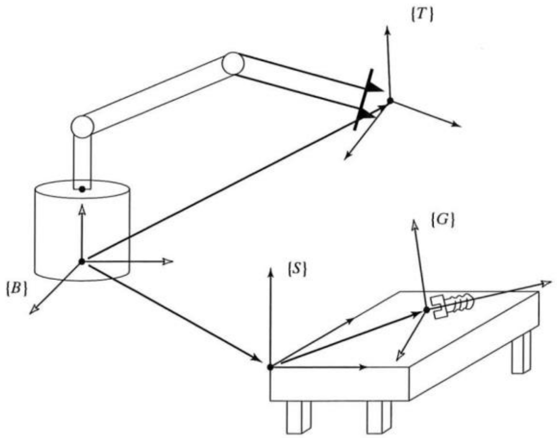


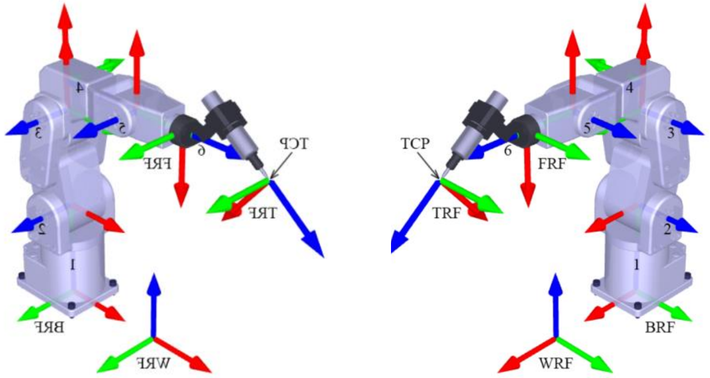
Registration

- **Registration -** The process of robot registration involves finding the location of a robot with respect to another reference frame.

    - **Robot / Parts - Example 1 -** if parts are in known locations on a table and a robot can locate itself with respect to the table (an external reference frame), then the robot will also know the location of the parts.

    - **Two Robotic Arms - Example 2 -** if two or more robots can locate themselves with respect to the table, then each robot will not only know the location of the parts, but also the location of every other robot. This knowledge facilitates the coordination of robot motions and robot collaboration and eases the integration of additional robots into the work cell.





Robotic Arm Architecture

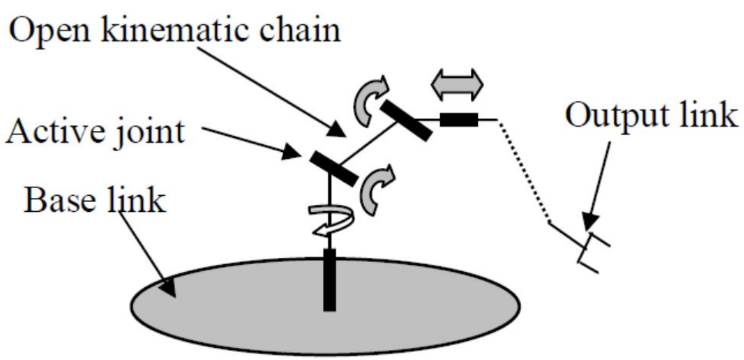
Serial Architecture

Parallel Architecture

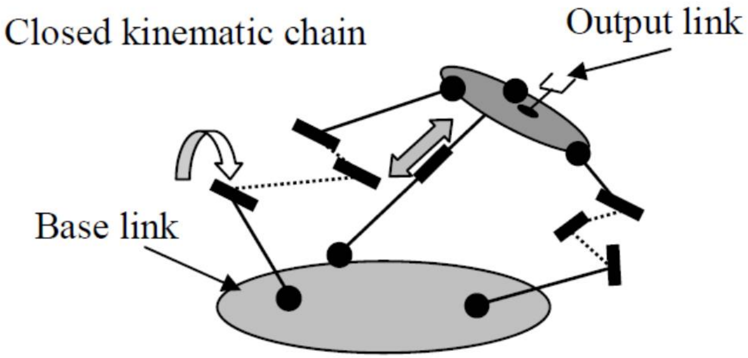
Anatomy – Mechanism Topology

https://www.youtube.com/watch?v=3fbmguBgVPA

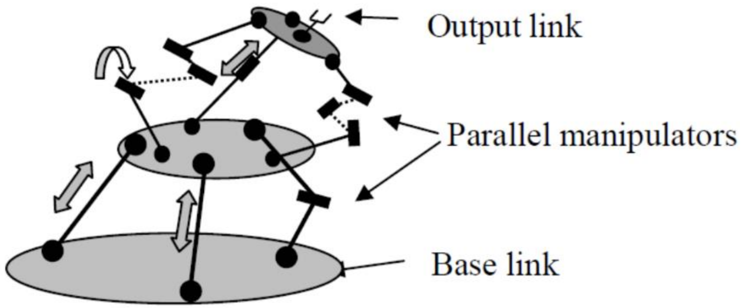
Robot Arm Anatomy



Serial Manipulator



Parallel Manipulator



Hybrid Manipulator

Comparison Table

Category	Property	Serial	Parallel
Mechanics	Type of Joints	Active (R, P)	Active & Passive (R,P,U,S)
Kinematics	Chain Type	Open	Close
	Role of Active Joint	Twist	Wrench
	Direct / Forward Kinematics	Simple	Complicated
	Inverse Kinematics	Complicated	Simple
	Multiple Solutions	Low (small number)	High (large number)
	Singularity	Loss of freedom	Gain of Freedom
	Singularity Location	Arm – Edge - Workspace Wrist - Inside & Edge - Workspace	Inside & Edge - Workspace
Dynamics	Inertia of Moving Parts	High	Low
	End Effector Speed	Low	High
Performance	Position Accuracy	Low	High
	Payload to Weight Ratio	Low	Very High
	Workspace (Volume)	High	Low
	Computational Power (needed)	Low	High

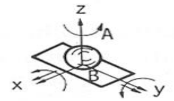
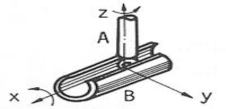
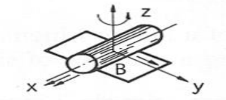
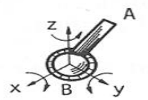
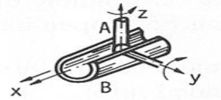
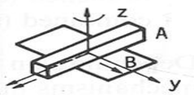
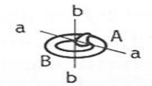
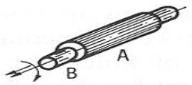
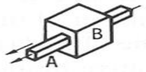
Robotic Arm Architecture

Joints

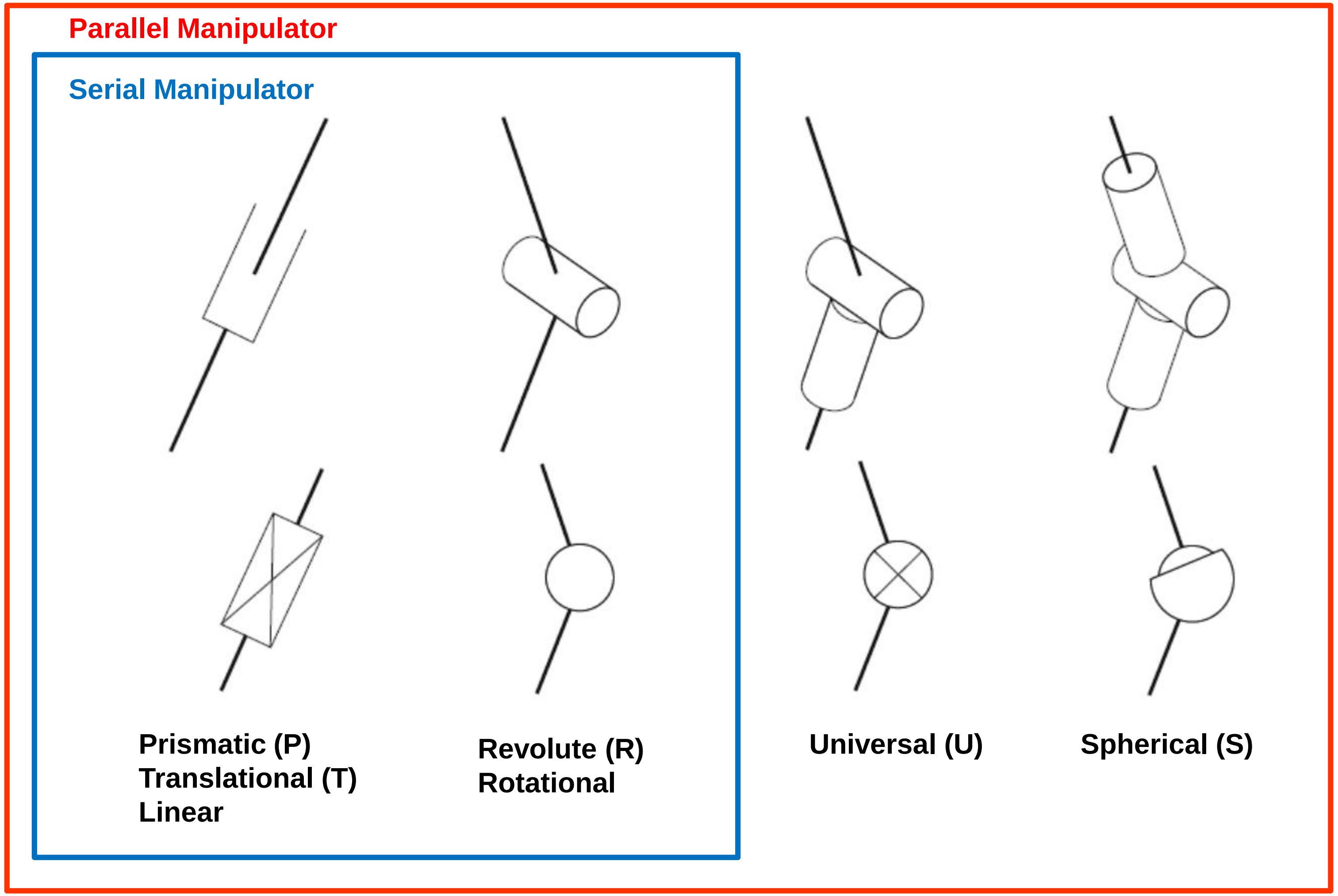
Comparison Table

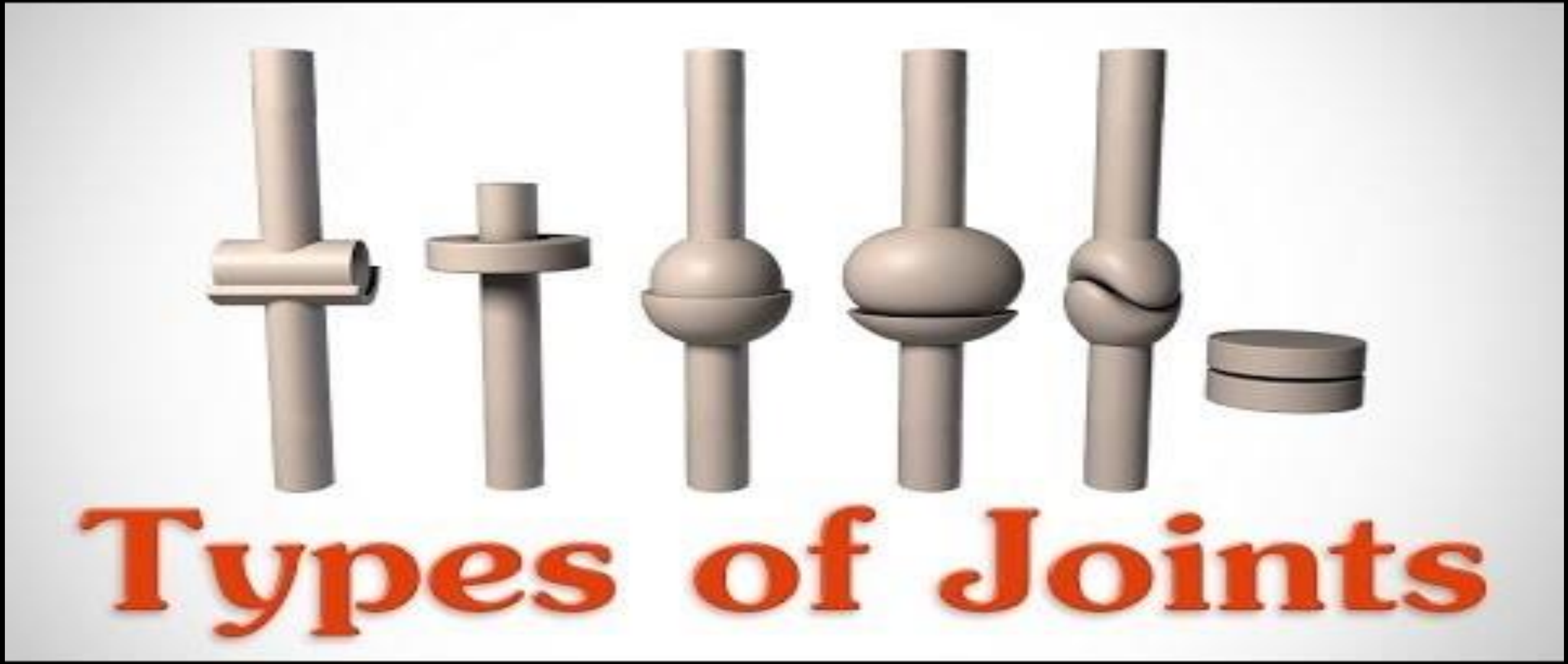
Category	Property	Serial	Parallel
Mechanics	Type of Joints	Active (R, P)	Active & Passive (R,P,U,S)
Kinematics	Chain Type	Open	Close
	Role of Active Joint	Twist	Wrench
	Direct / Forward Kinematics	Simple	Complicated
	Inverse Kinematics	Complicated	Simple
	Multiple Solutions	Low (small number)	High (large number)
	Singularity	Loss of freedom	Gain of Freedom
	Singularity Location	Arm – Edge - Workspace Wrist - Inside & Edge - Workspace	Inside & Edge - Workspace
Dynamics	Inertia of Moving Parts	High	Low
	End Effector Speed	Low	High
Performance	Position Accuracy	Low	High
	Payload to Weight Ratio	Low	Very High
	Workspace (Volume)	High	Low
	Computational Power (needed)	Low	High

Joint Classification

class of task	nr. of links	nr. of d.o.f.	TYPES OF PAIRS: I	TYPES OF PAIRS: II	TYPES OF PAIRS: III
I	1	5	nr. of movem. / rot. / lin. allowed / 3 / 2 restricted / 0 / 1 		
II	2	4	nr. of movem. / rot. / lin. allowed / 3 / 1 restricted / 0 / 2 	nr. of movem. / rot. / lin. allowed / 2 / 2 restricted / 1 / 1 	
III	3	3	nr. of movem. / rot. / lin. allowed / 3 / 0 restricted / 0 / 3 	nr. of movem. / rot. / lin. allowed / 2 / 1 restricted / 1 / 2 	nr. of movem. / rot. / lin. allowed / 1 / 2 restricted / 2 / 1 
IV	4	2	nr. of movem. / rot. / lin. allowed / 2 / 0 restricted / 1 / 3 	nr. of movem. / rot. / lin. allowed / 1 / 1 restricted / 2 / 2 	
V	5	1	nr. of movem. / rot. / lin. allowed / 1 / 0 restricted / 2 / 3 	nr. of movem. / rot. / lin. allowed / 0 / 1 restricted / 3 / 2 	

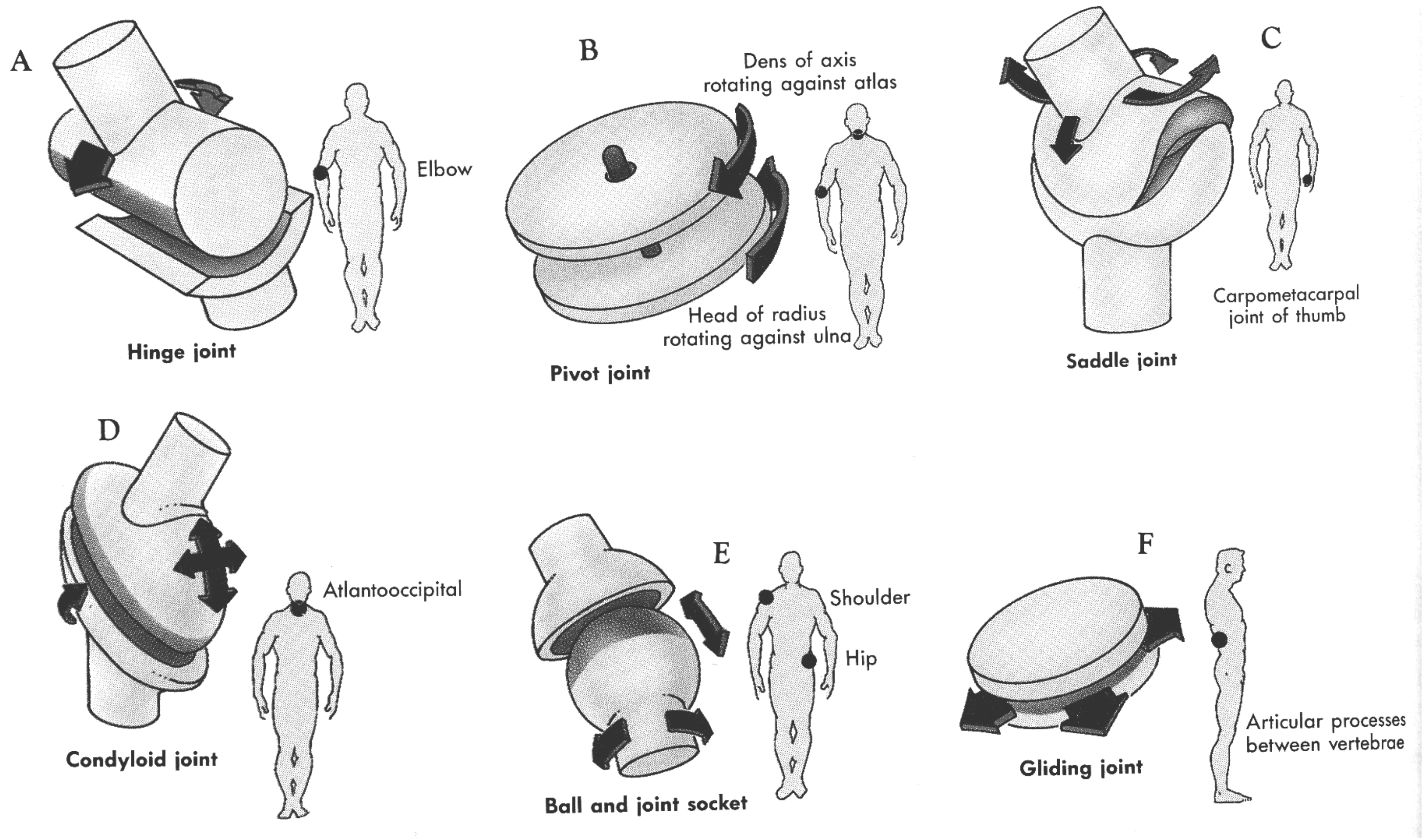
Joint Classification





The 6 Types of Joints - Human Anatomy

Synovial (Anatomical) Joints



Robotic Arm Architecture

Kinematic Chain

Connection between Links and Joints

Comparison Table

Category	Property	Serial	Parallel
Mechanics	Type of Joints	Active (R, P)	Active & Passive (R,P,U,S)
Kinematics	Chain Type	Open	Close
	Role of Active Joint	Twist	Wrench
	Direct / Forward Kinematics	Simple	Complicated
	Inverse Kinematics	Complicated	Simple
	Multiple Solutions	Low (small number)	High (large number)
	Singularity	Loss of freedom	Gain of Freedom
	Singularity Location	Arm – Edge - Workspace Wrist - Inside & Edge - Workspace	Inside & Edge - Workspace
Dynamics	Inertia of Moving Parts	High	Low
	End Effector Speed	Low	High
Performance	Position Accuracy	Low	High
	Payload to Weight Ratio	Low	Very High
	Workspace (Volume)	High	Low
	Computational Power (needed)	Low	High

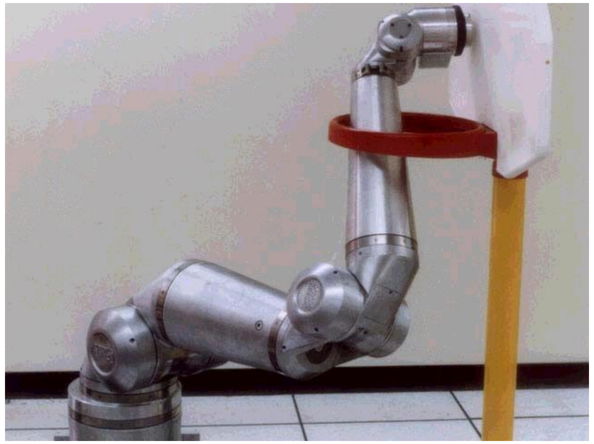
Kinematic Chain - Joint / Link - Definition

Kinematic Chain consists of nearly rigid *links (members)* which are connected with *joints (kinematics pair)* allowing relative motion of the neighboring links.

Closed Loop Chain - Every link in the kinematic chain is connected to any other link by at least two distinct paths

Open Loop Chain - Every link in the kinematic chain is connected to any other link by one and only one distinct path

Parallel (Close Loop) Robot

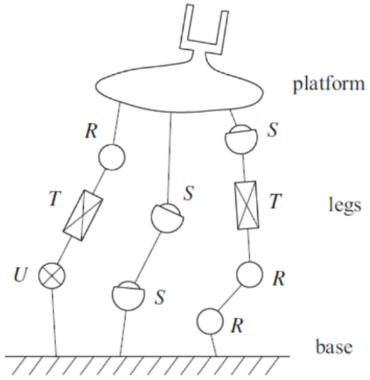


Serial (Open Loop) Robot Video Hyperlink

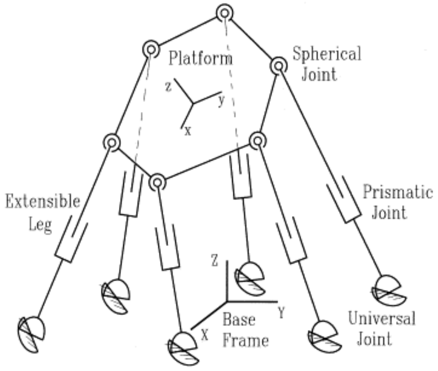
Robotic Arm Architecture

Naming Convention

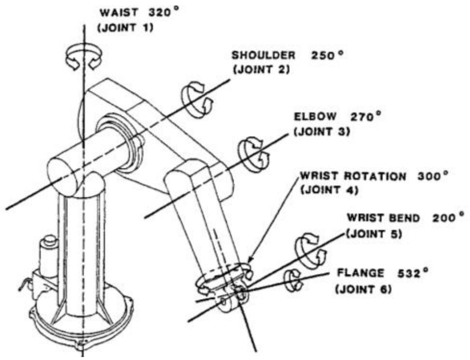
Manipulator Naming Convention



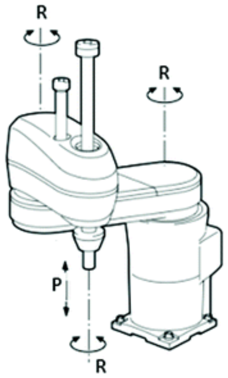
UTR-SS-RRTS



6 UTS (Gough–Stewart platform)



6R – RRRRRR (Puma 560)



3RPR – RRRPR (SCARA)

Robotic Arm Architecture

Degrees of Freedom (DOF)

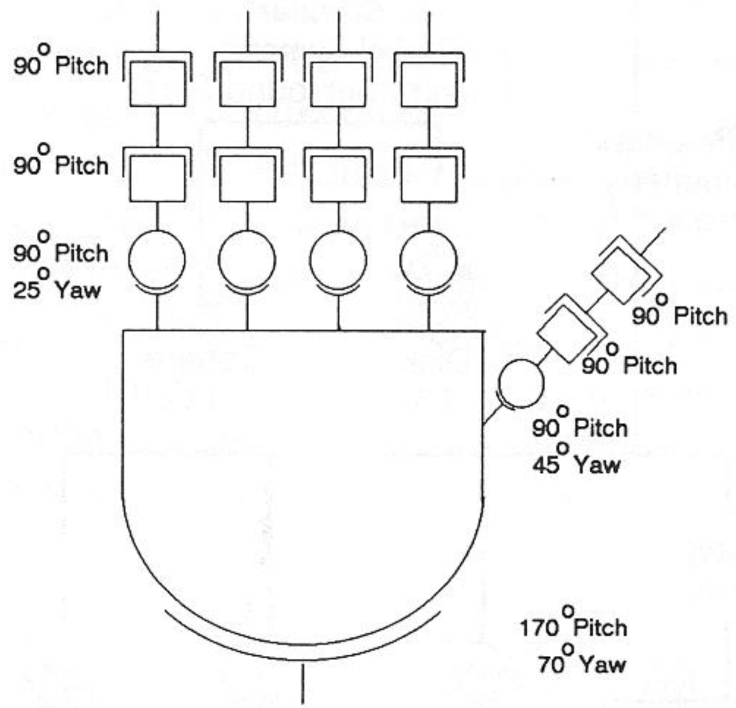
Degrees of Freedom (DOF)

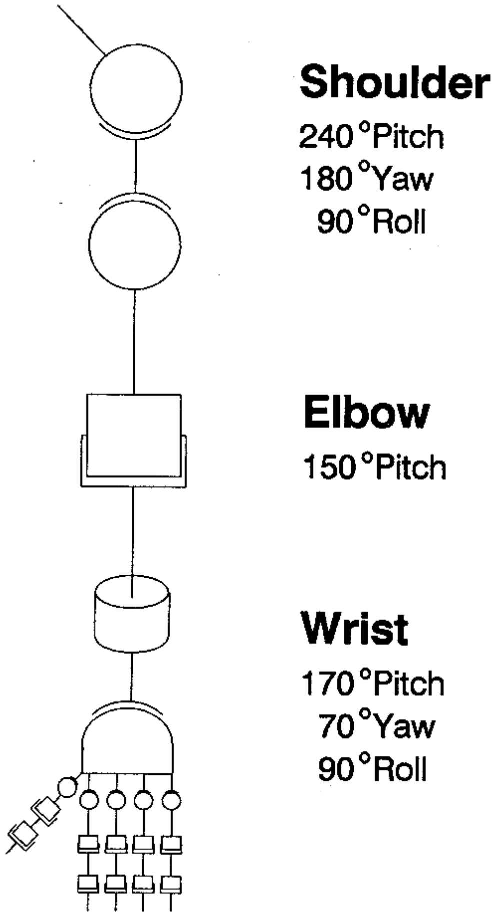
The number of ***Degree of Freedom*** that a manipulator possesses is the number independent position variable which would have to be specified in order to locate all parts of the mechanism.

Ideally, a manipulator should posses 6 DOF in order to manipulate an object in a 3D space

- **General Purpose Robot** - # DOF = 6
- **Redundant Robot** - # DOF >7
- **Deficient Robot** - # DOF < 6

Human Arm - DOF





Robotic Arm Architecture

Workspace

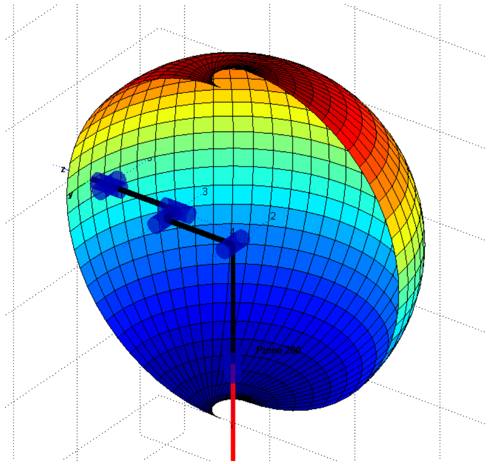
Workspace - Definition

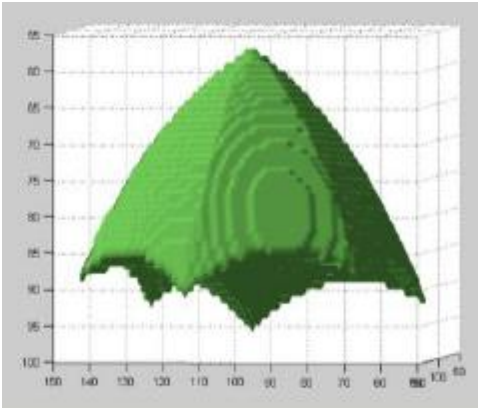
- **Workspace** - The volume of space that the end-effector can reach
- **Dexterous Workspace** - The volume of the space which every point can be reach by the end effector in all possible orientations.
- **Reachable Workspace** - The volume of the space which every point can be reach by the end effector in at least one orientation.

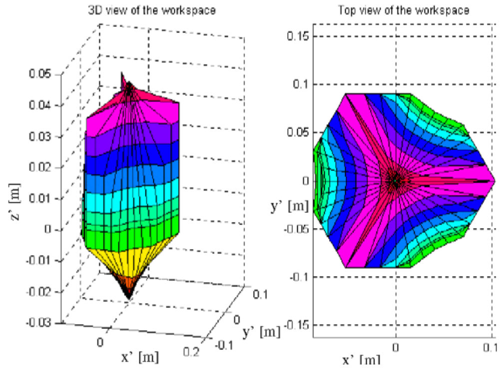
Comparison Table

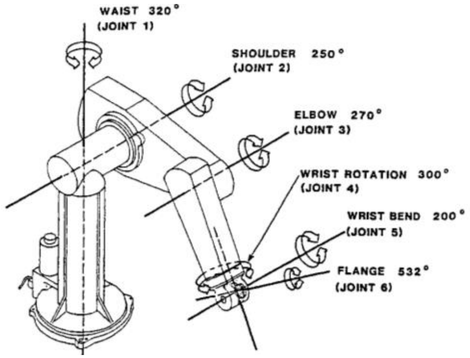
Category	Property	Serial	Parallel
Mechanics	Type of Joints	Active (R, P)	Active & Passive (R,P,U,S)
Kinematics	Chain Type	Open	Close
	Role of Active Joint	Twist	Wrench
	Direct / Forward Kinematics	Simple	Complicated
	Inverse Kinematics	Complicated	Simple
	Multiple Solutions	Low (small number)	High (large number)
	Singularity	Loss of freedom	Gain of Freedom
	Singularity Location	Arm – Edge - Workspace Wrist - Inside & Edge - Workspace	Inside & Edge - Workspace
Dynamics	Inertia of Moving Parts	High	Low
	End Effector Speed	Low	High
Performance	Position Accuracy	Low	High
	Payload to Weight Ratio	Low	Very High
	Workspace (Volume)	High	Low
	Computational Power (needed)	Low	High

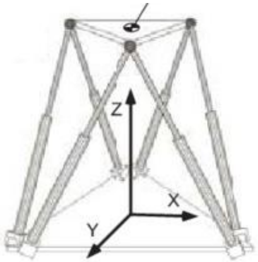
Workspace – Serial versus Parallel Archtecture

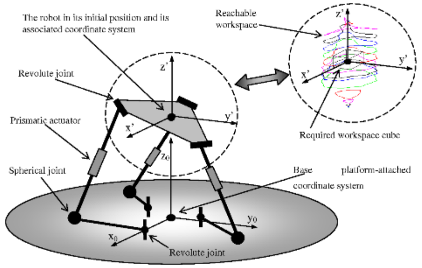












Serial Architecture

Serial Architecture – Summary

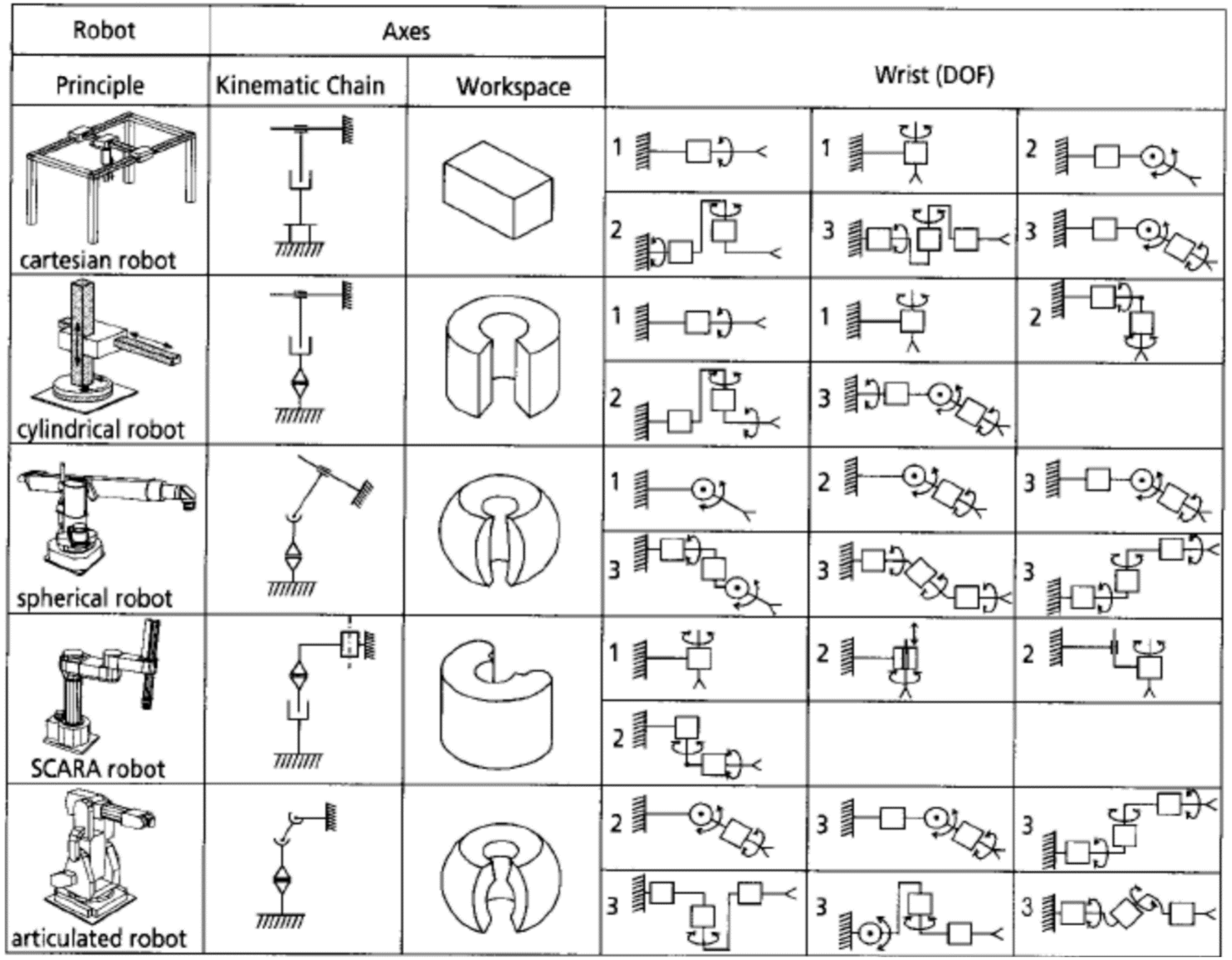
PPP

RPP

RRP

RRP

RRR



Jointed Spherical Arm Geometry (Articularted)

Serial Architecture – Summary

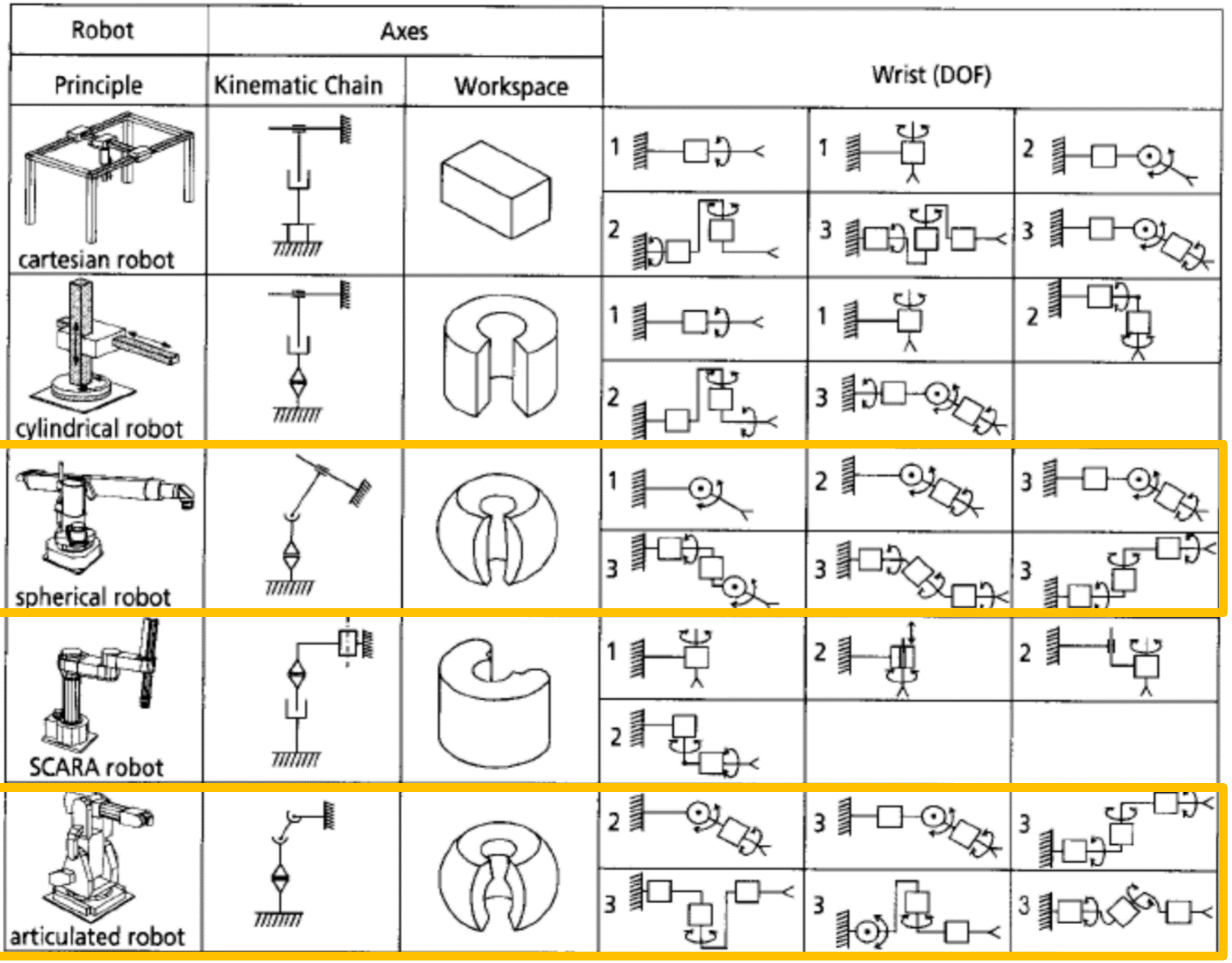
PPP

RPP

RRP

RRP

RRR



Serial Manipulators – Historical Perspective

PUMA – Unimate
1960

Stanford Arm
1969

Serial Architecture – Summary

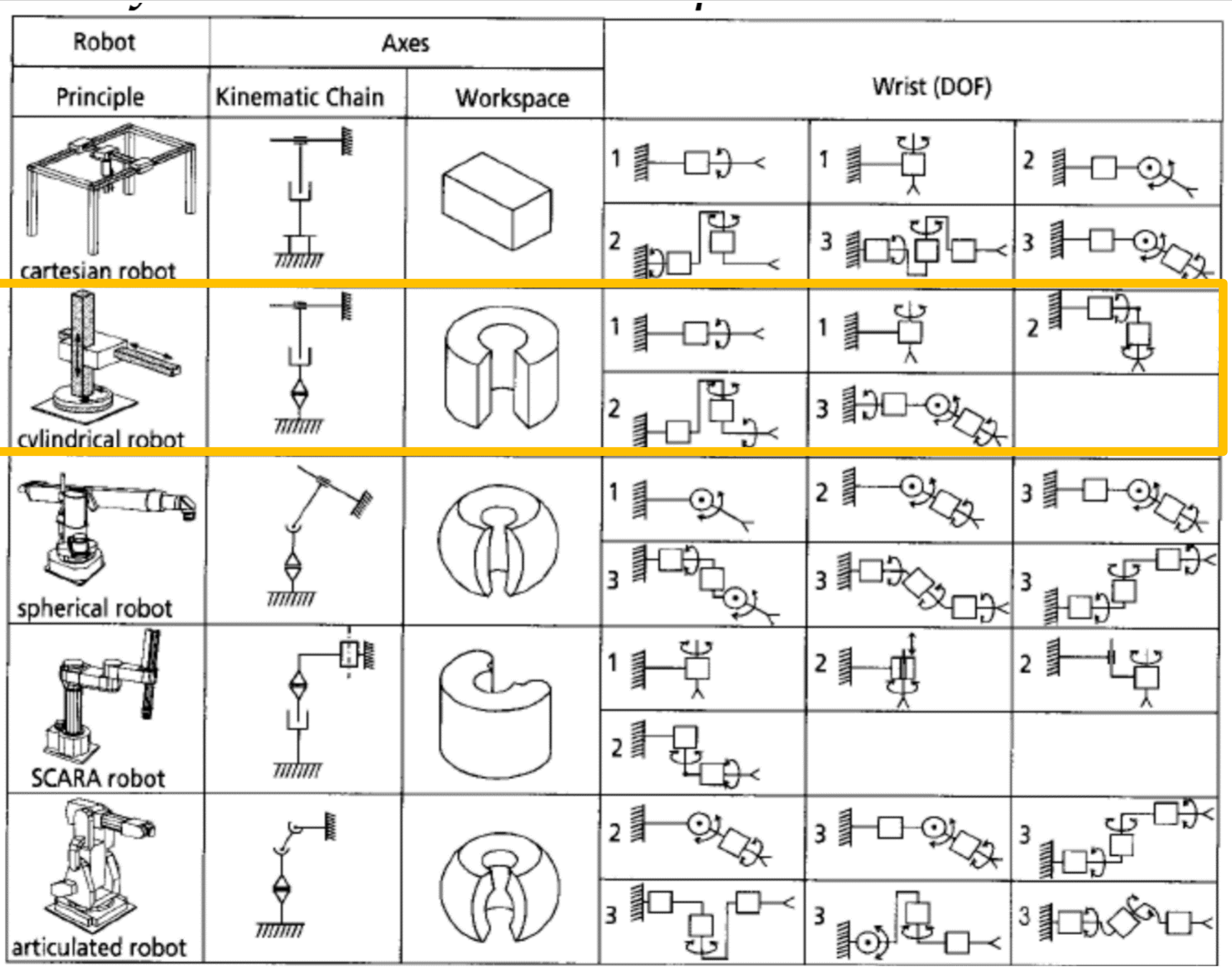
PPP

RPP

RRP

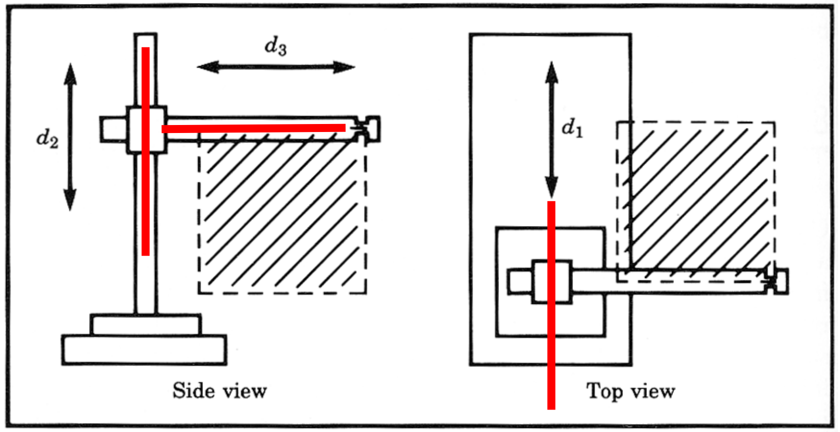
RRP

RRR



Kinematic Configuration – Cartesian (3P)

- **Joints**
  - Joint 1 - Prismatic
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic



- **Inverse Kinematics** - Trivial

- **Structure -**
  - Stiff Structure -> Big Robot
  - Decoupled Joints - No singularities

- **Disadvantage**
  - All feeder and fixtures must lie “inside” the robot

Serial Architecture – Summary

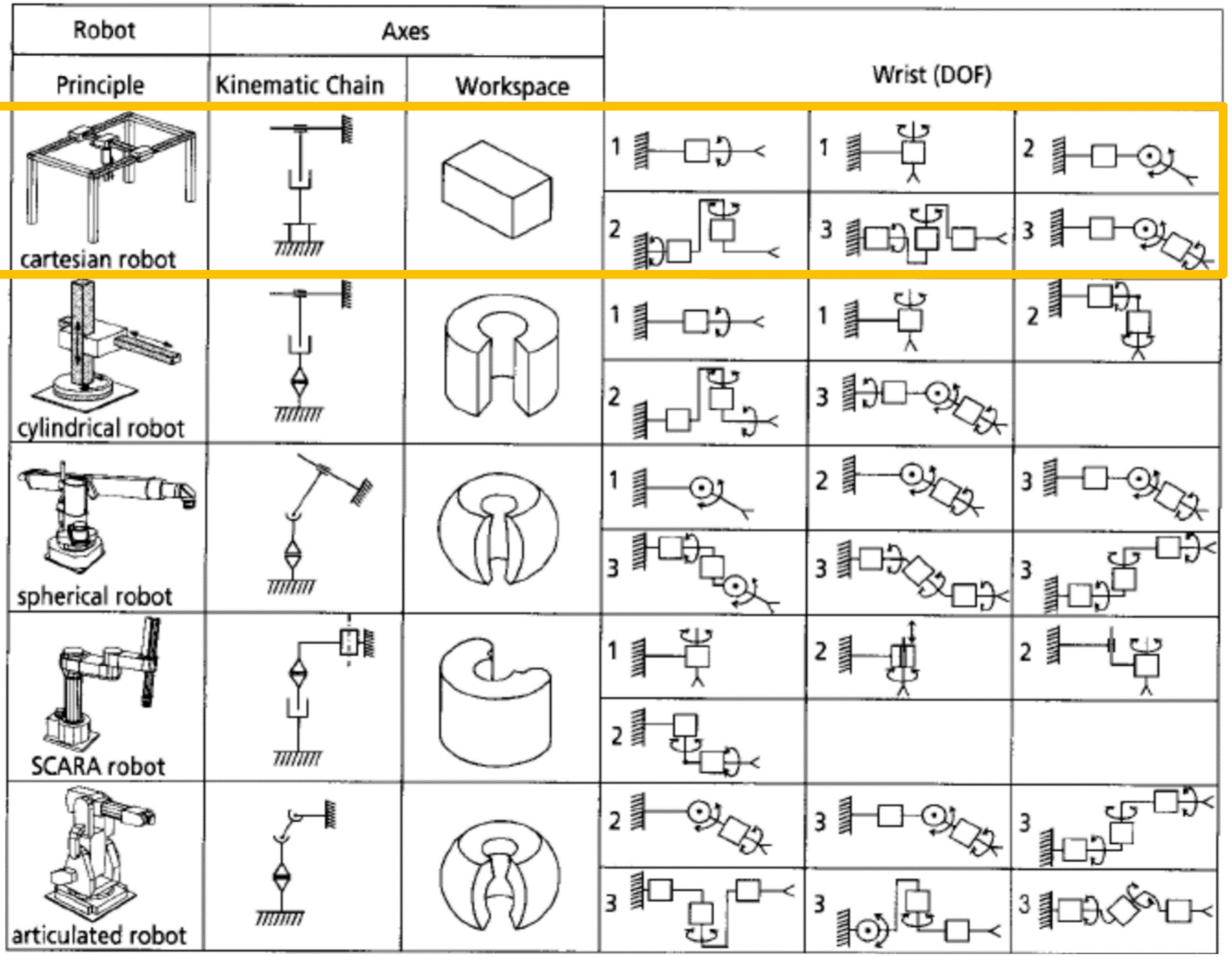
PPP

RPP

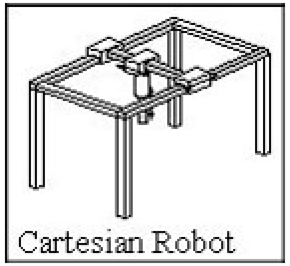
RRP

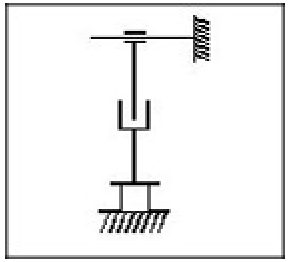
RRP

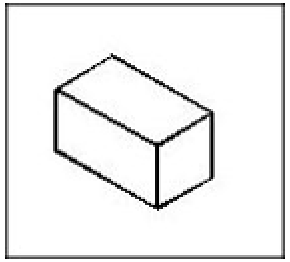
RRR

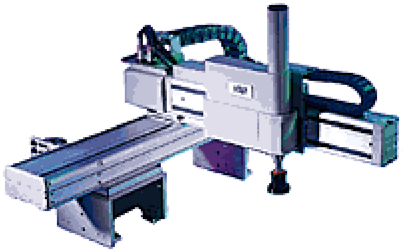


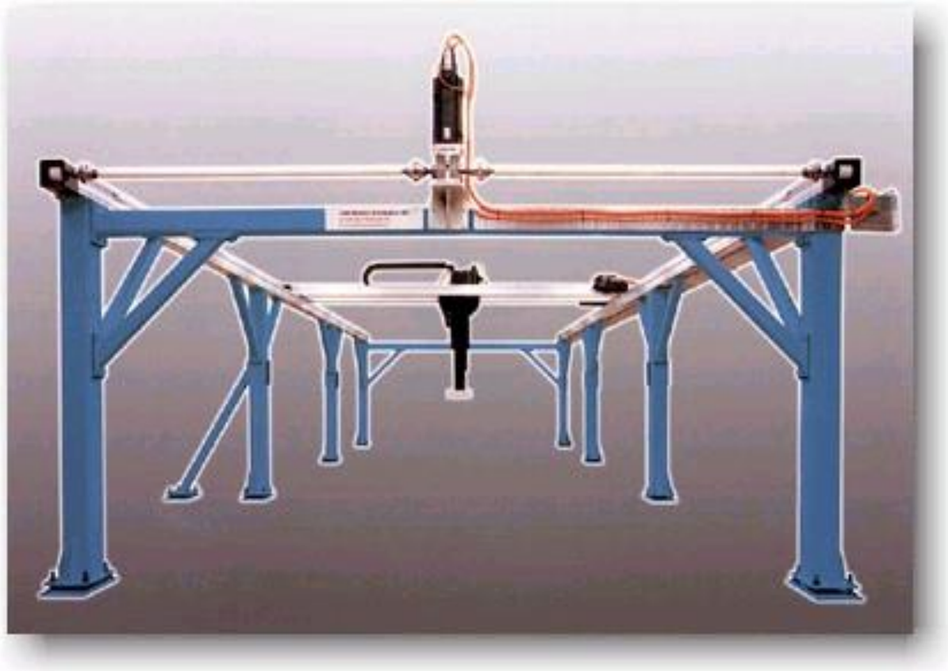
Kinematic Configuration - Cartesian



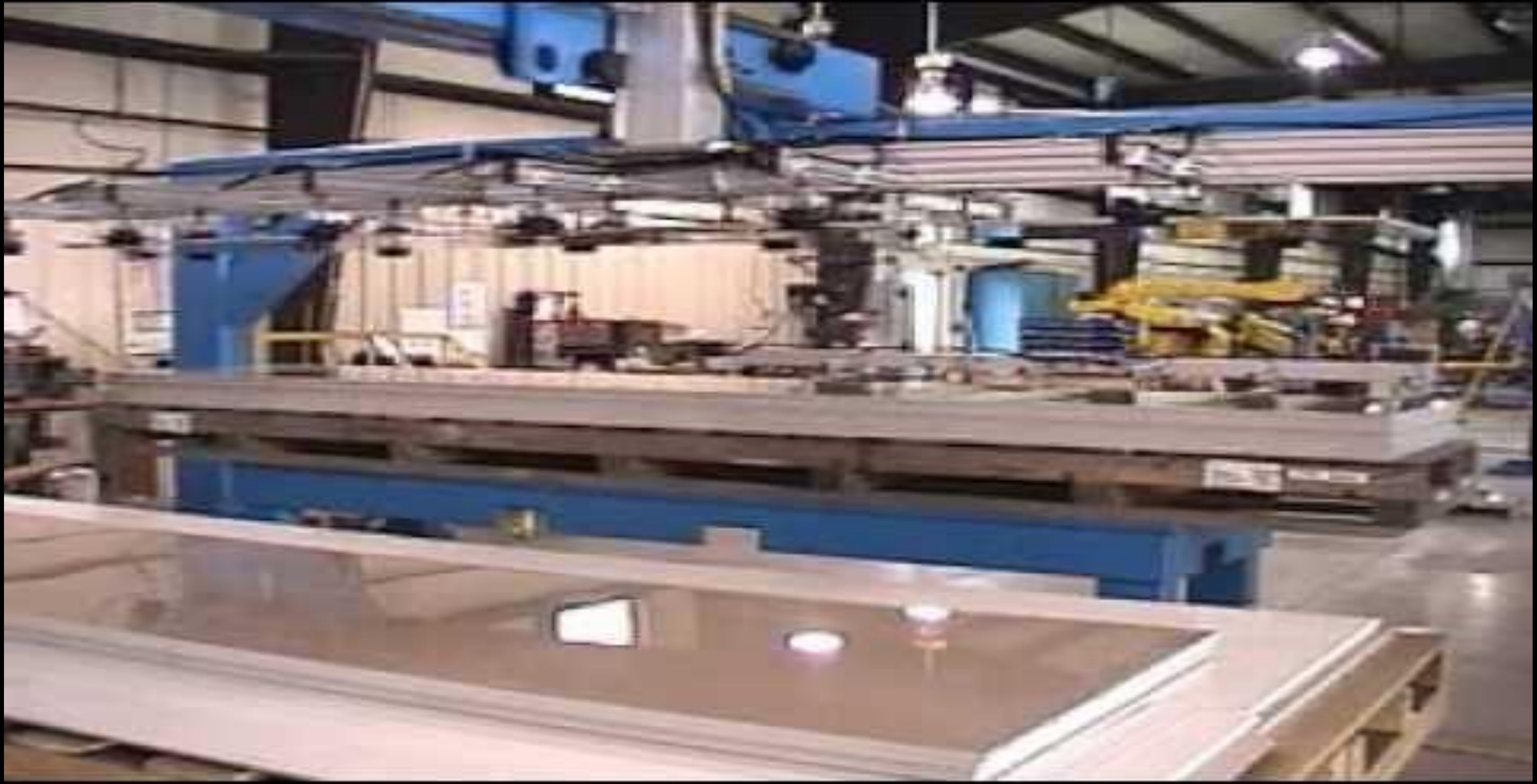








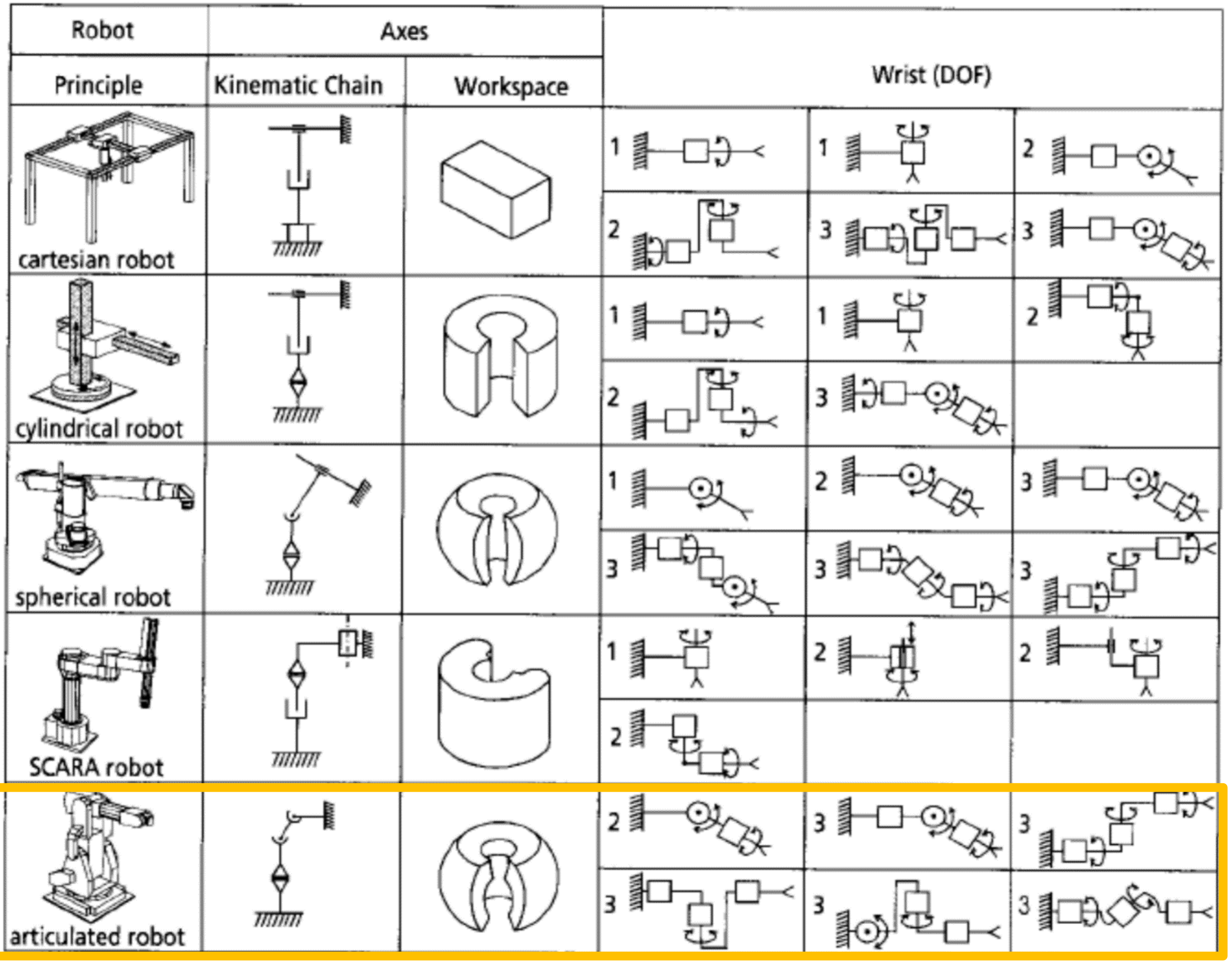
Gantry



Gantry Robot - Solid surface countertop stacking

Serial Architecture – Summary

PPP	
RPP	
RRP	
RRP	
RRR	

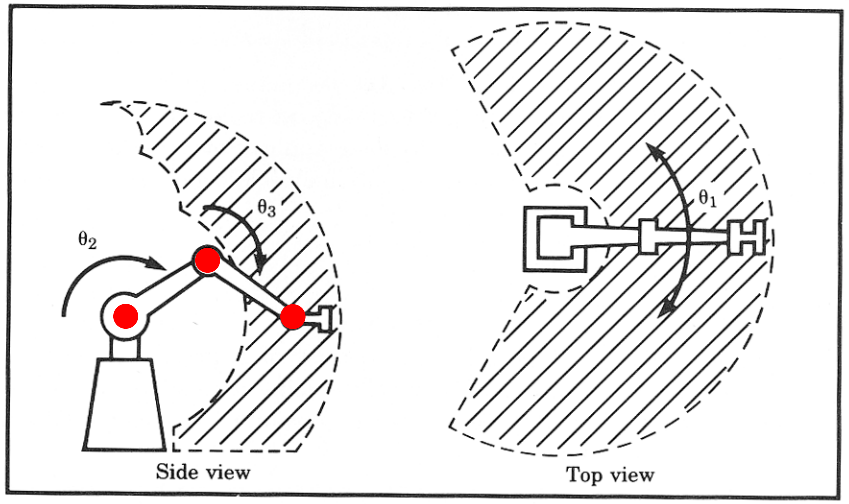


Kinematic Configuration – Articulated (3R)

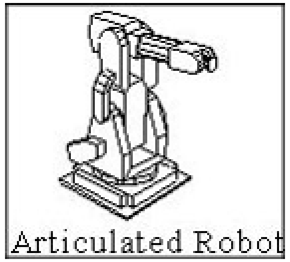
- **Joints**
  - Joint 1 - Revolute -Shoulder
  - Joint 2 - Revolute - Elbow
  - Joint 3 - Revolute - Wrist

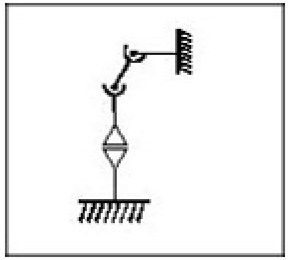
- **Workspace**
  - Minimal intrusion
  - Reaching into confine spaces
  - Cost effective for small workspace

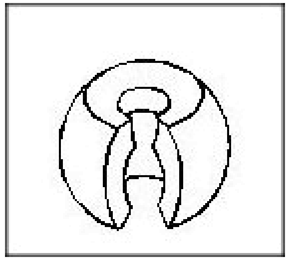
- **Examples**
  - PUMA
  - MOTOMAN



Kinematic Configuration - Articulated







Video Clip

Fanuc – Full Human Body

Serial Architecture – Summary

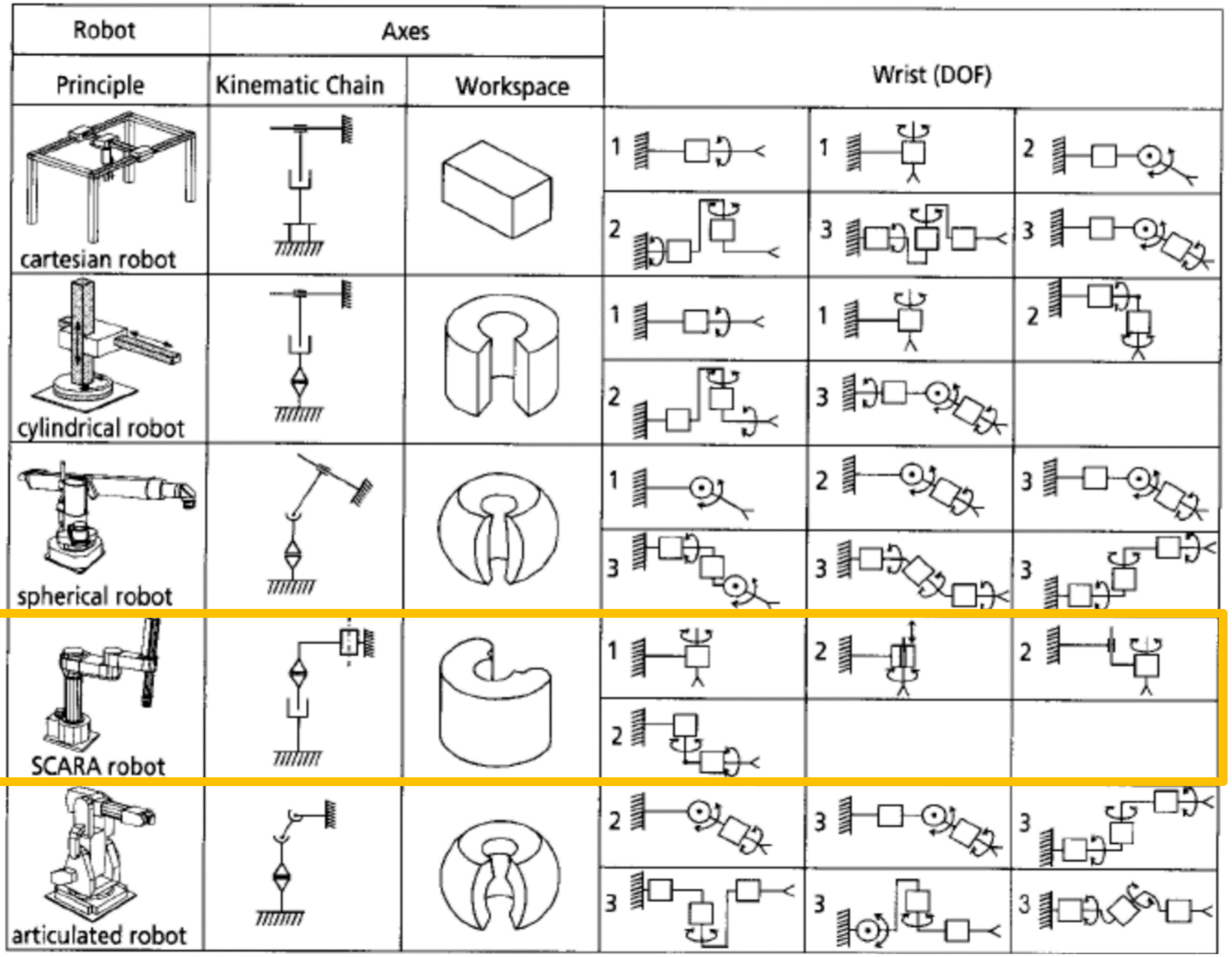
PPP

RPP

RRP

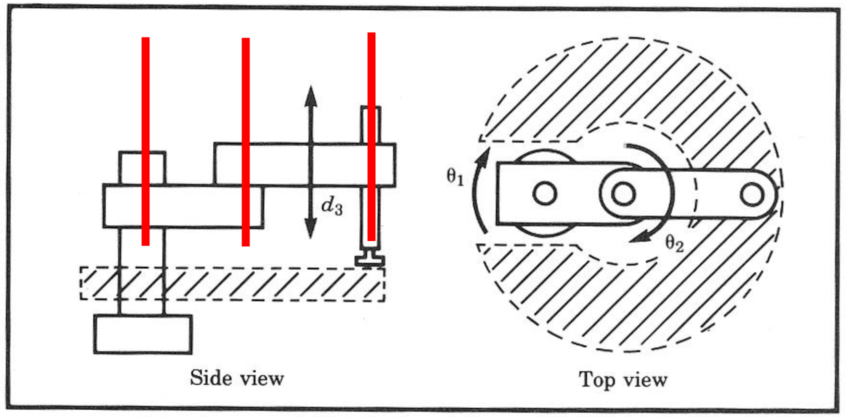
RRP

RRR



Kinematic Configuration – SCARA (3RPR)

- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Revolute
  - Joint 3 - Revolute
  - Joint 4 - Prismatic
  - Joint 1,2,3 - In plane

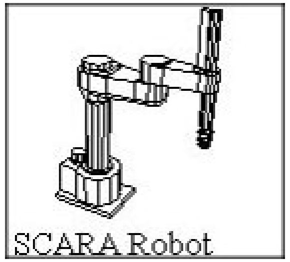


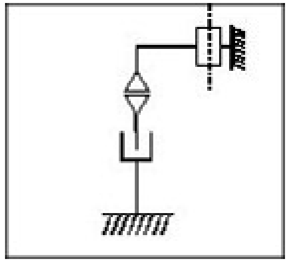
- **Structure**
  - Joint 1,2,3, do not support weight (manipulator or weight)
  - Link 0 (base) can house the actuators of joint 1 and 2

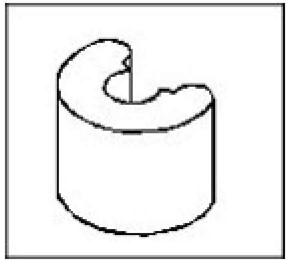
- **Speed**
  - High speed (10 m/s), 10 times faster then the most articulated industrial robots

- **Example** - SCARA (Selective Compliant Assembly Robot Arm)

Kinematic Configuration - SCARA







Kawasaki Robot-Painting Robots

Serial Architecture – Summary

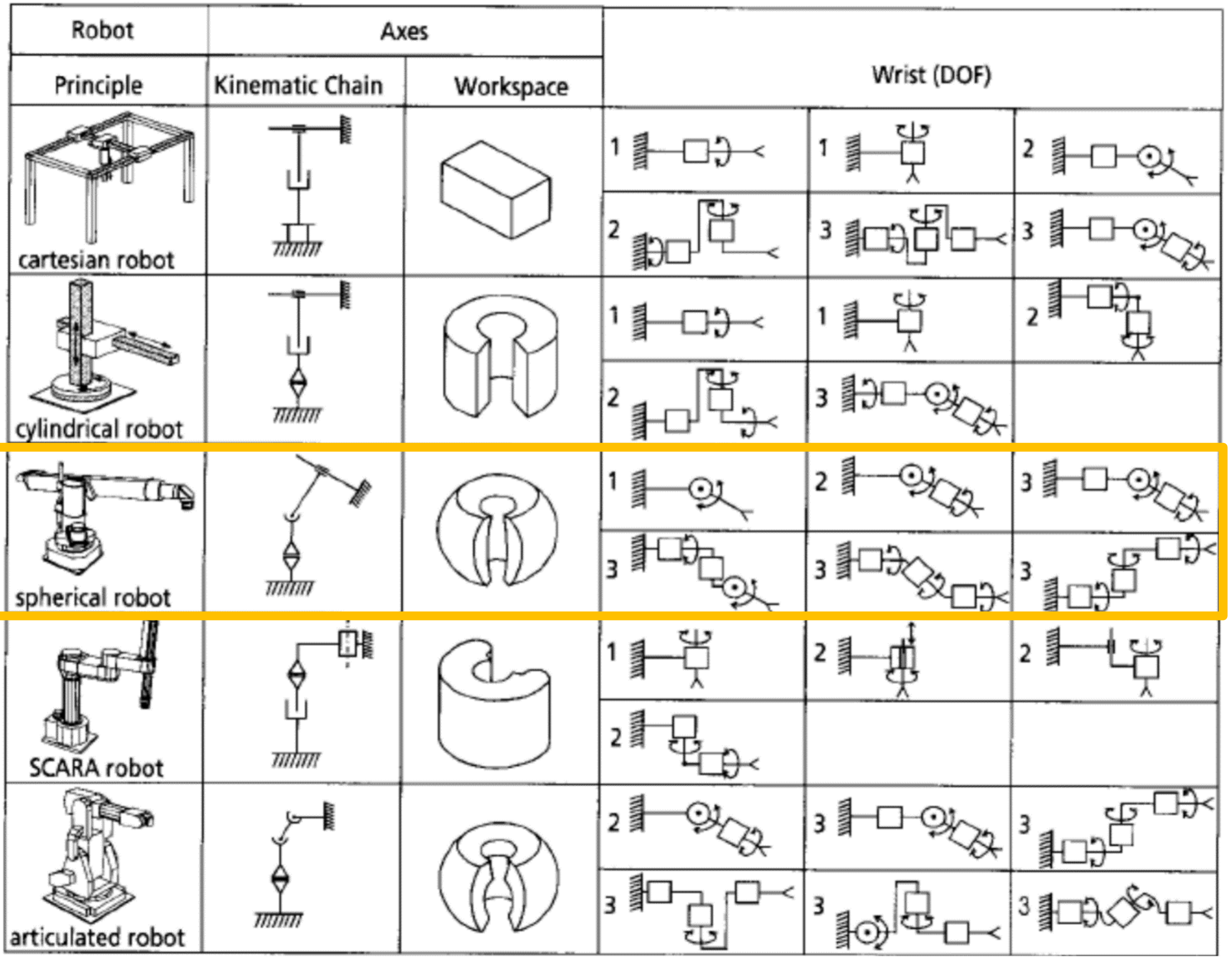
PPP

RPP

RRP

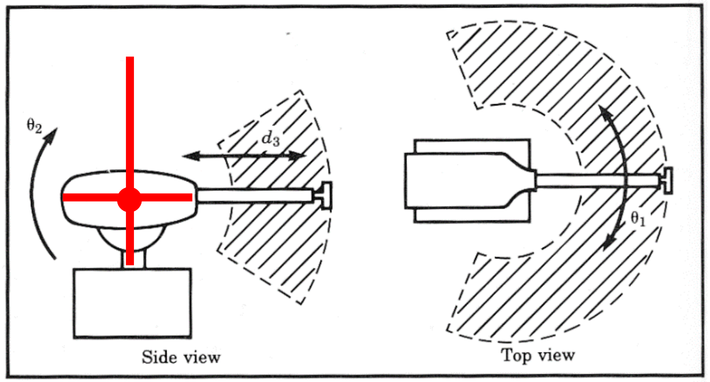
RRP

RRR



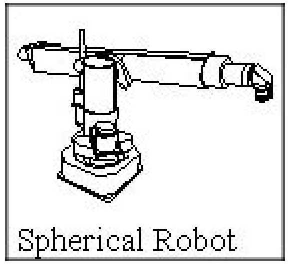
Kinematic Configuration – Spherical (RRP)

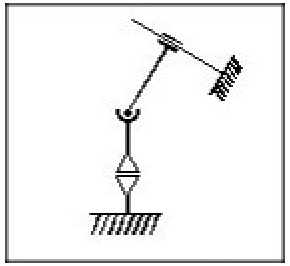
- **Joints**
  - Joint 1 - Revolute (Intersect with 2)
  - Joint 2 - Revolute (Intersect with 1)
  - Joint 3 - Prismatic

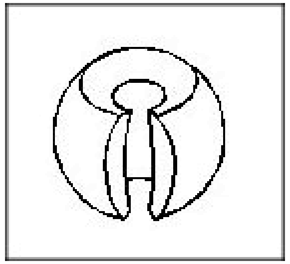


- **Structure**
  - The elbow joint is replaced with prismatic joint
  - Telescope

Kinematic Configuration - Spherical







Stanford Arm

Serial Architecture – Summary

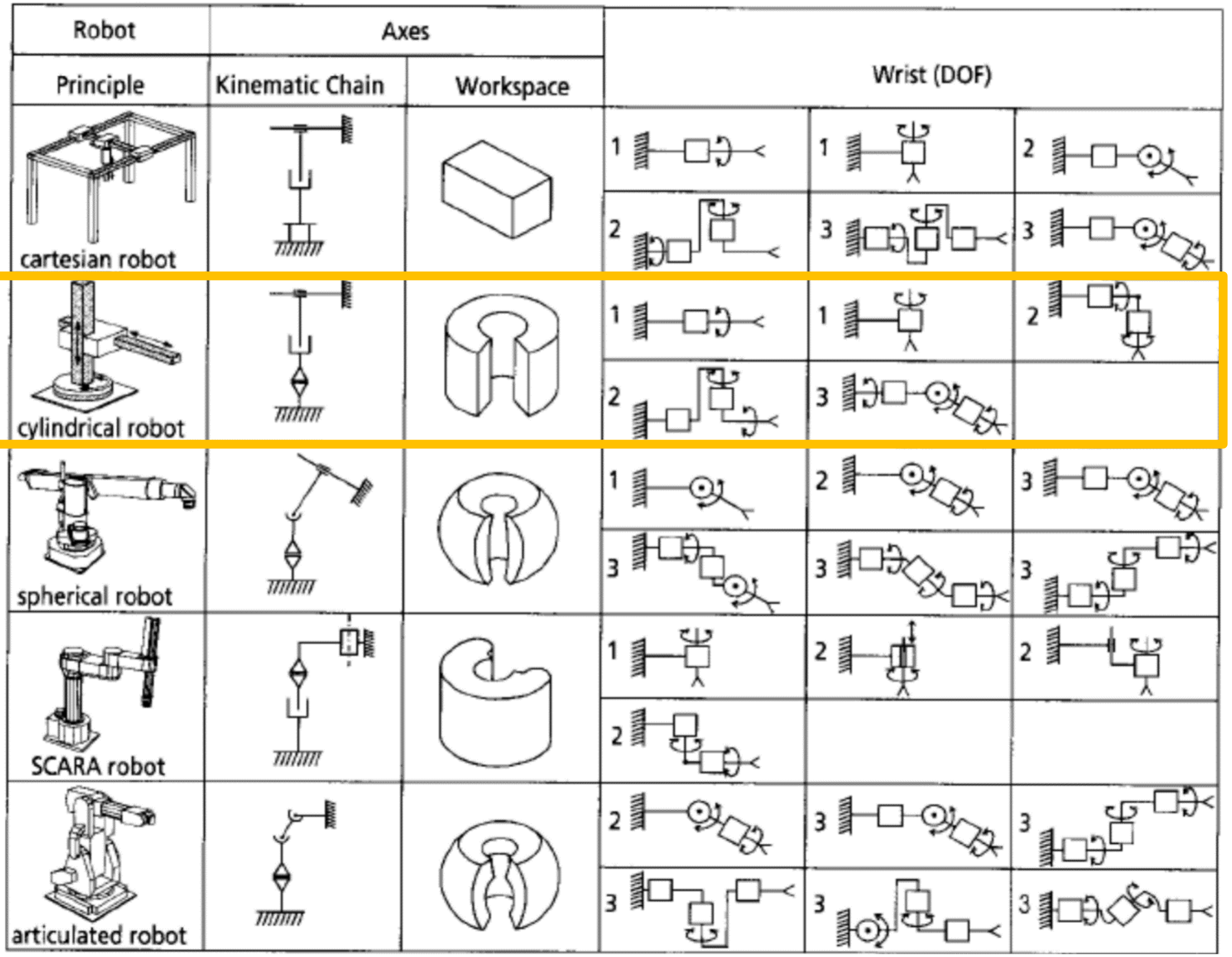
PPP

RPP

RRP

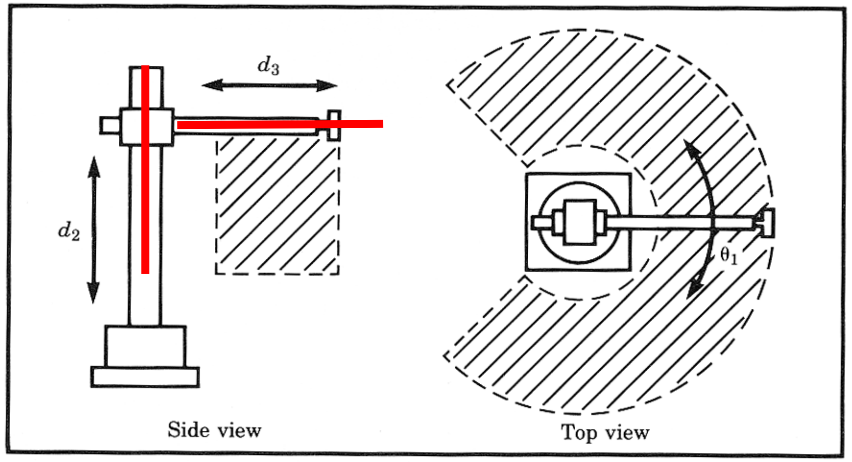
RRP

RRR

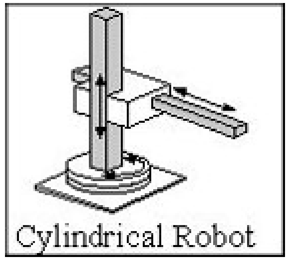


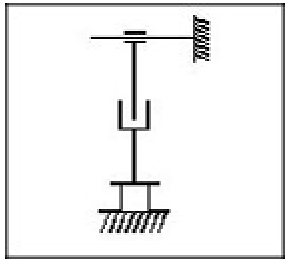
Kinematic Configuration – Cylindrical (RPP)

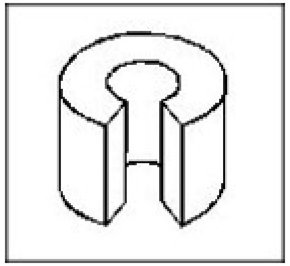
- **Joints**
  - Joint 1 - Revolute
  - Joint 2 - Prismatic
  - Joint 3 - Prismatic

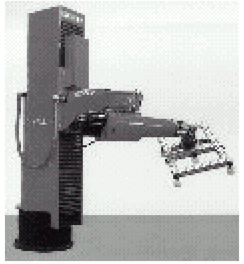


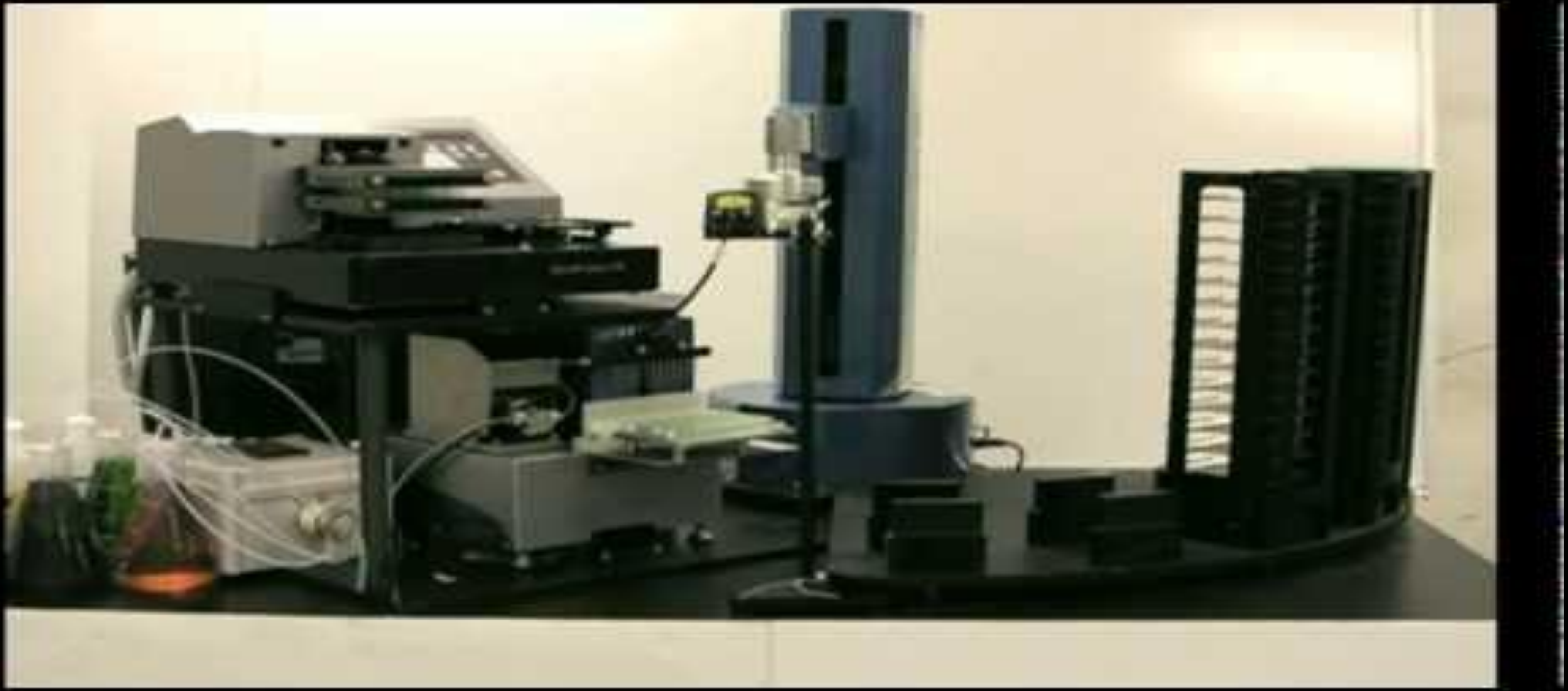
Kinematic Configuration - Cylindrical



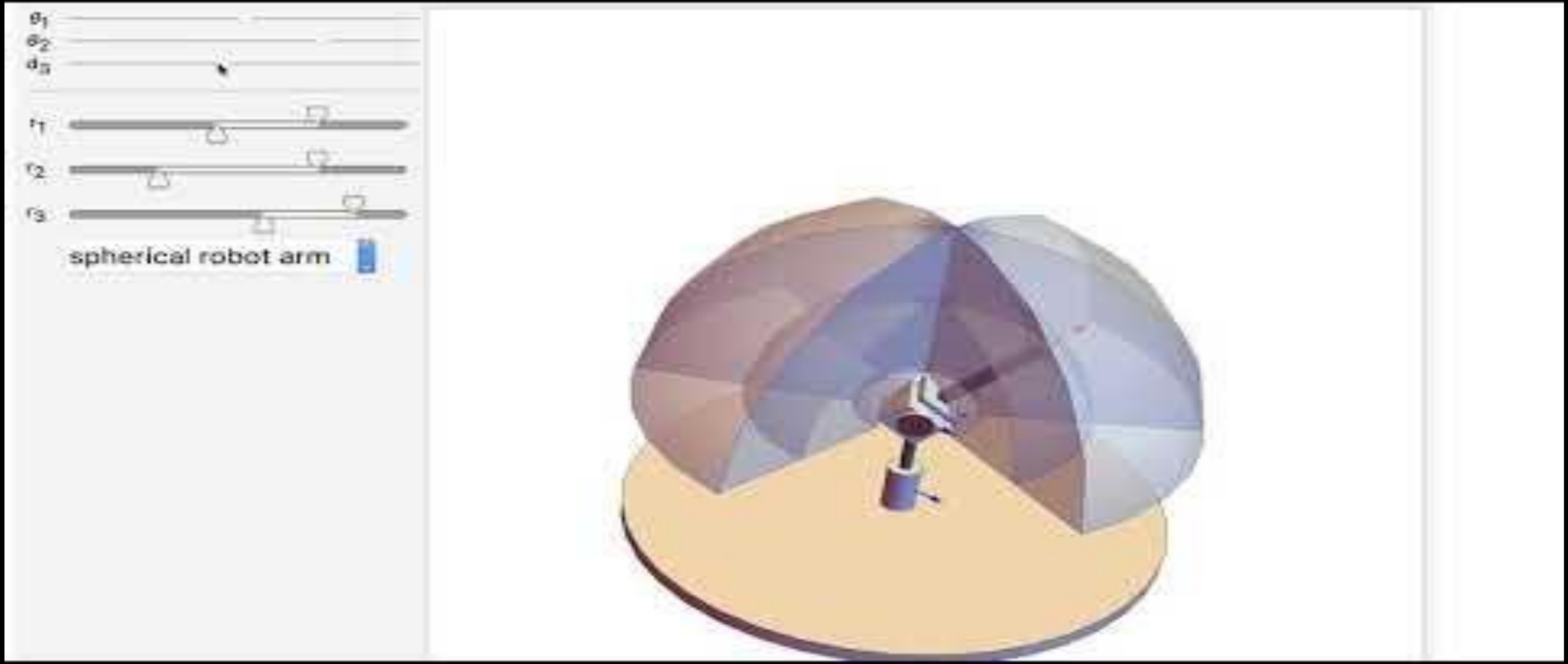






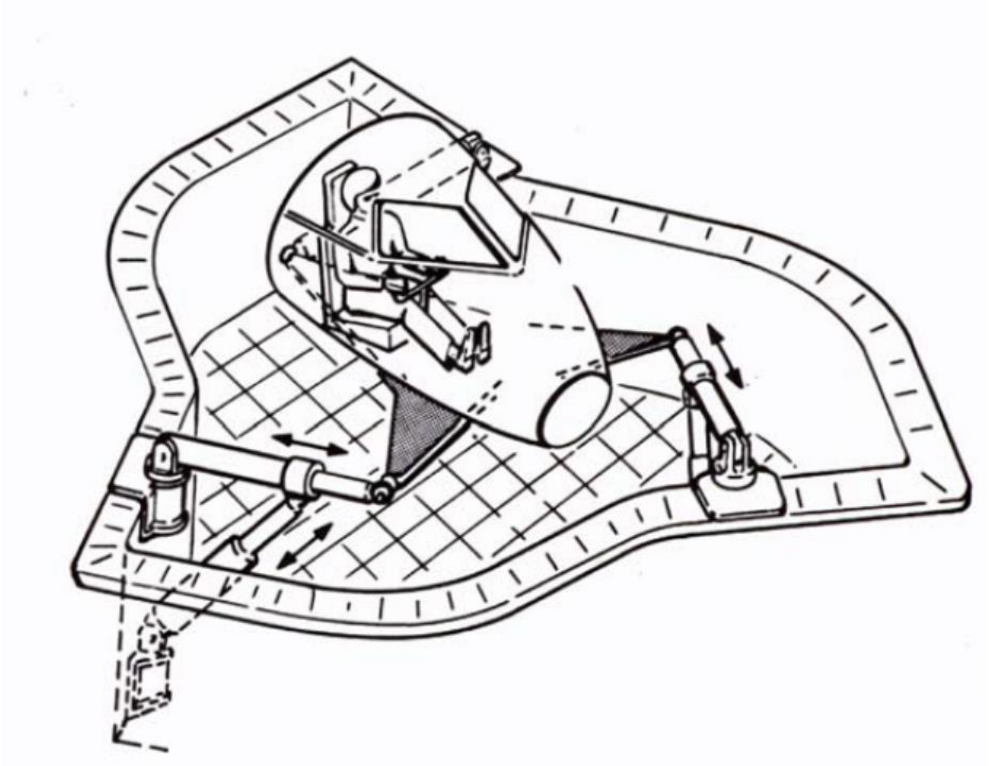


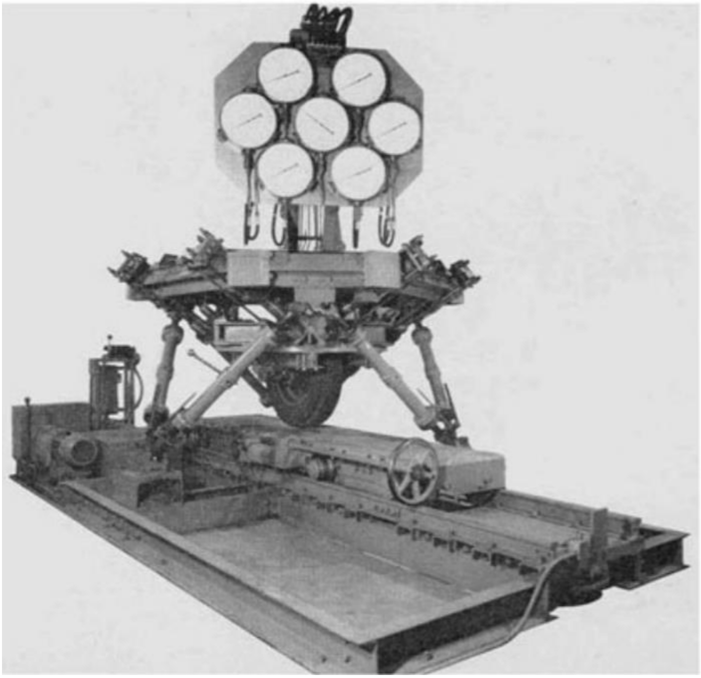
Robotic Arm Geometry


θ1
θ2
d3
r1
r2
r3
spherical robot arm

Parallel Architecture

Parallel Architecture – Historical Perspective

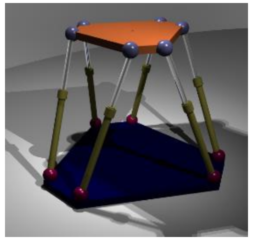


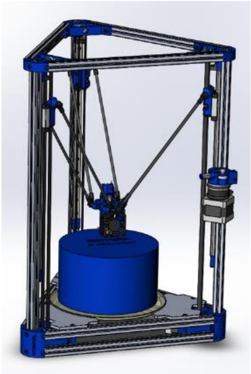


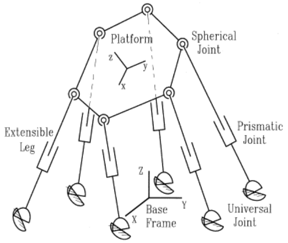
Flight Simulator Concept
Stewart 1965

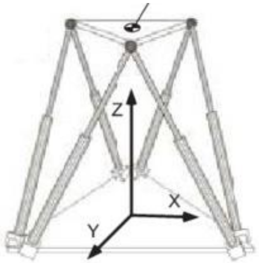
Tyre under the action of combined loads
Gough 1957;
Gough and Whitehall 1962

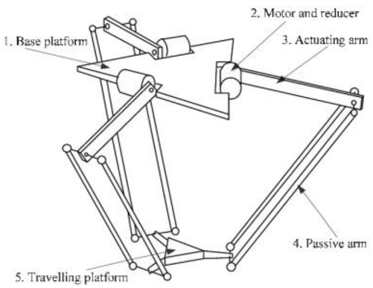
Parallel Architecture – Common Architectures











6 UTS
(Gough–Stewart platform)
6 DOF

3 T4S (parallelogram)
Delta
3 DOF

3 R4S (parallelogram)
Delta
3 DOF

Parallel Robot – Gough-Stewart Platform – Thomas FX Motion Base

https://youtu.be/xiECumcaEx0

Parallel Robot – Delta Robot - Adept Quattro Robot handling steel balls on conveyor

Close Chain Manipulators - DOF

- DOF of close chain manipulator – Grubler's formula

$$F = 6(l - n - 1) + \sum_{i=1}^{n} f_i$$

  - F - The total number of DOF in the mechanism
  - l - The number of links (including the base and the platform)
  - n - Total number of joints
  - f_i - The number of DOF associated with the i'th joint

- Example – Stewart Platform

$$F = 6(14 - 18 - 1) + \sum_{i=1}^{6} 6 = 6$$

Close Chain Manipulators - Gough-Stewart Platform

Parallel Robot – Gough-Stewart Platform - A320 Full Flight Simulator – Part I

Parallel Robot – Gough-Stewart Platform - A320 Full Flight Simulator – Part II

Wrist Architecture

Kinematic Configuration - Wrist

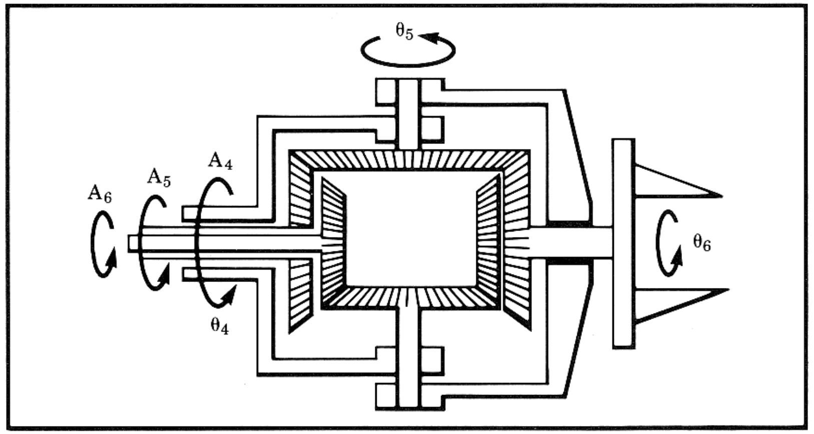
- **Joints**
  - Three (or two) joints with orthogonal axes

- **Workspace**
  - Theoretically - Any orientation could be achieved (Assuming no joint limits)
  - Practically - Severe joint angle limitations

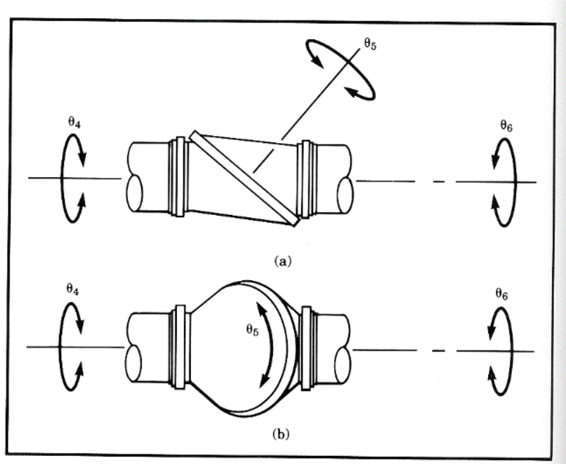
- **Kinematics**
  - Closed form kinematic equations

Kinematic Configuration - Wrist

- Three intersecting orthogonal Axes
  Bevel Gears Wrist
- Limited Rotations



- Three Roll Wrist (Cincinatti Milacron)
- Three intersecting non-orthogonal Axes
- Continues joint rotations (no limits)
- Sets of orientations which are impossible to reach



Kinematic Configuration - Wrist

- 5 DOF Welding robot (2 DOF wrist) - Symmetric tool
- The tool axis $\hat{Z}_T$ is mounted orthogonal to axis 5 in order to reach all possible orientations

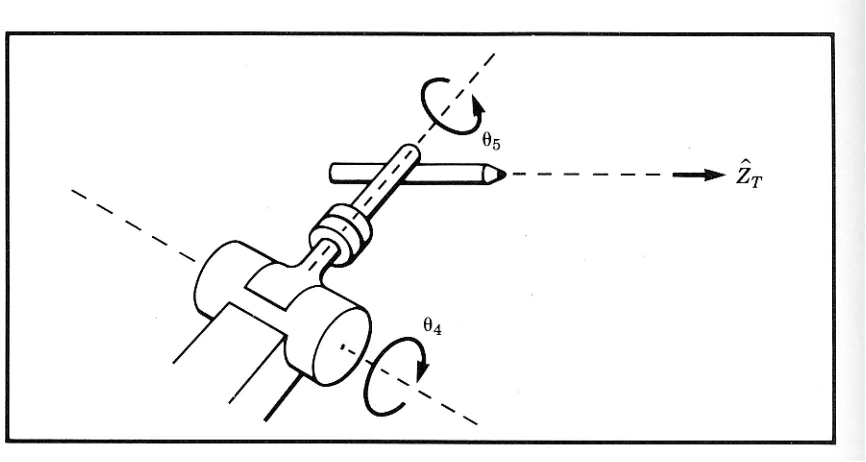
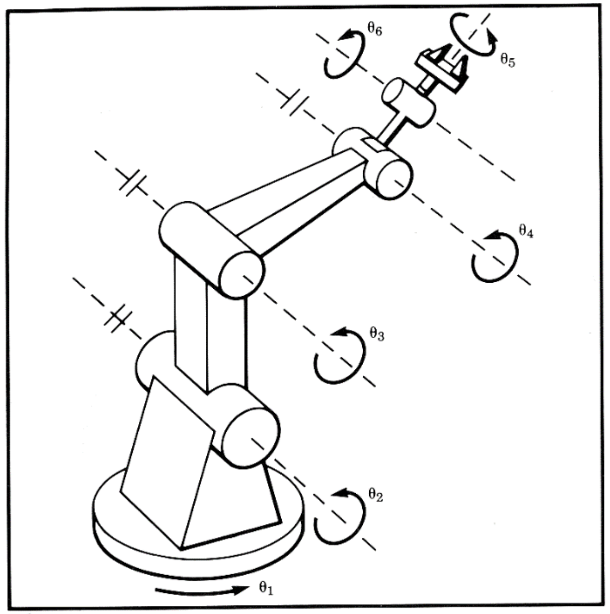


ABB Robotics - Arc Welding

- **Non intersecting axes wrist**
  - A closed form inverse kinematic solution may not exist

- **Special Cases** (Existing Solution)
  - Articulated configuration - Joint axes 2,3,4 are parallel
  - Cartesian configuration - Joint axes 4,5,6 do not intersect



Kuka KR 500 wrist mechanics - Axis 4, 5 & 6

Manipulability

Manipulability – Human Arm Posture - Writing

- Arm posture during writing
  - Elbow joint angle – 90 Deg

- Human arm model (writing)
  - 2 DOF
  - Two links (equal length)

- Manipulability is maximized when the Elbow joint angle is set to 90 Deg
  - Maximizing joint angles (shoulder /elbow) to end effector (hand) velocity transformation

Redundancy

Redundant Manipulators

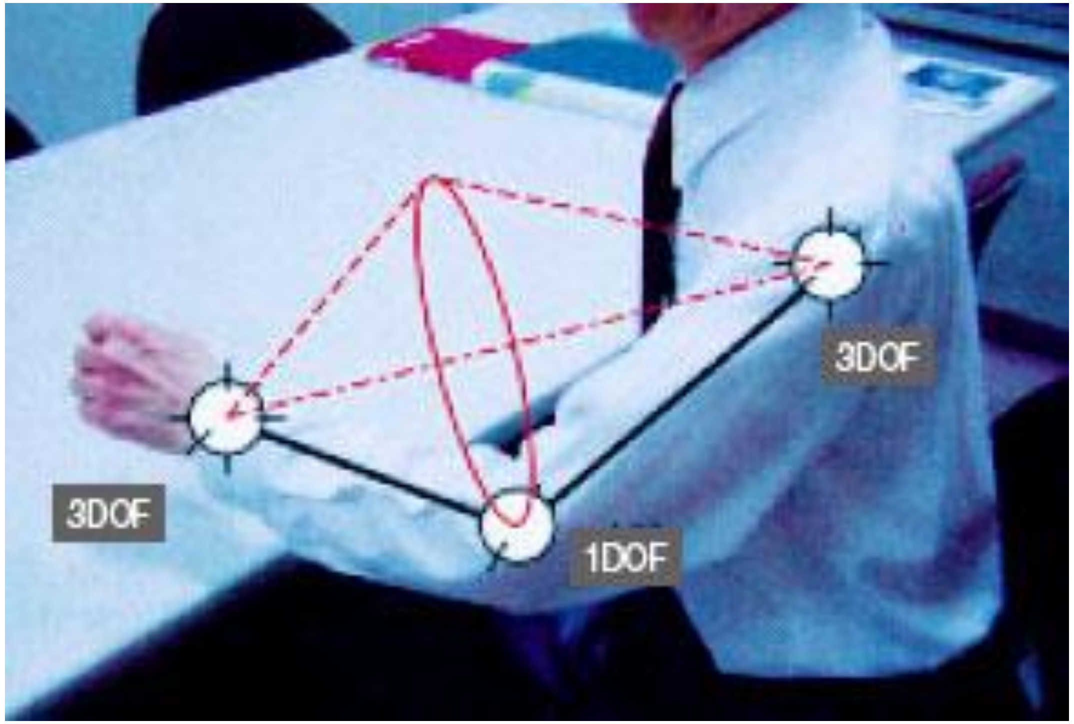
- Task Definition - Position (3 DOF - x, y, z) and orient the end effector (3 DOF $\theta_{pitch}, \theta_{roll}, \theta_{yaw}$)) in is a 3D space (6 DOF)

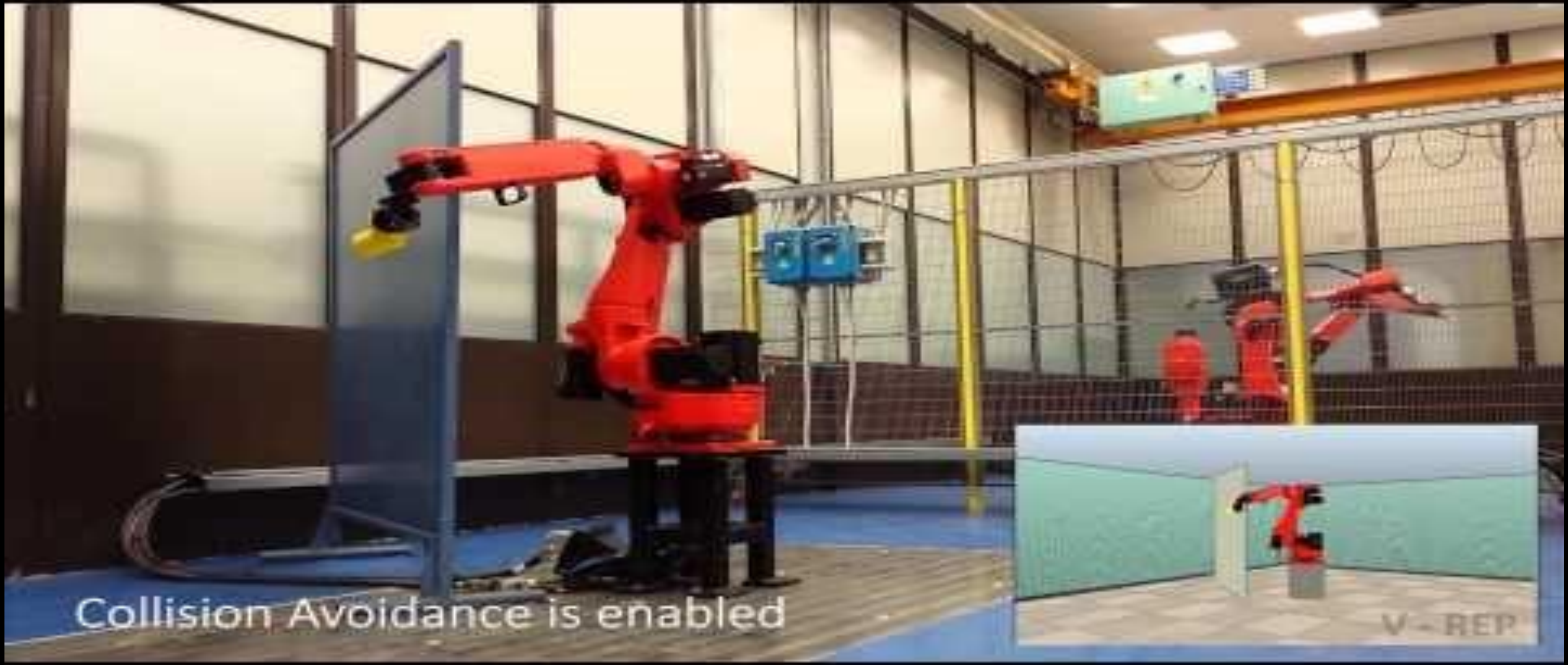
- No. of DOF (6 DOF) = No. of DOF of the task (6 DOF)
  - Limited number of multiple solutions

- No. of DOF (e.g. 7 DOF) > No. of DOF of the task (6 DOF)
  - Number of solution: ∞ (adding more equations)
  - Self Motion - The robot can be moved without moving the end effector from the goal

∞

Redundant Manipulators – Human Arm





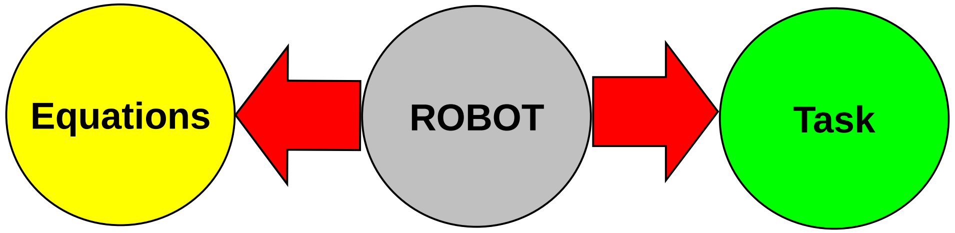
Collision avoidance: tests with a 7-dof redundant robot and a static obstacle

KUKA - Kinematic Redundancy

Design

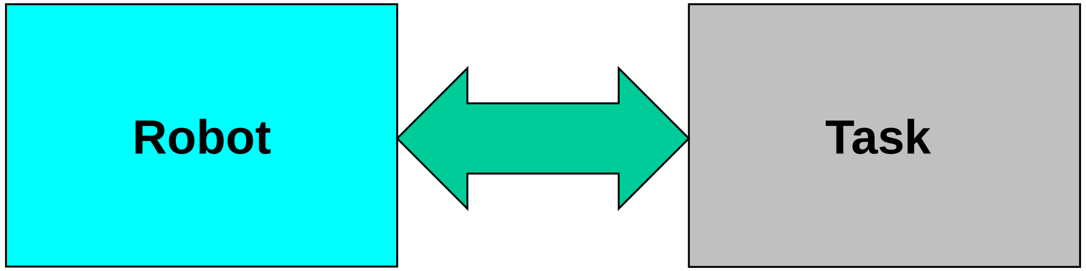
Manipulator Mechanical Design

- **Particular structure of a manipulator influences the kinematic and dynamic analysis**
- **The tasks that a manipulator can perform will also very greatly with a particular design (load capacity, workspace, speed, repeatability)**



- **The elements of a robotic system fall roughly into four categories**
  - The manipulator mechanism, actuation, and proprioceptive sensors
  - The end-effector or end of the arm tooling
  - External sensors (e.g. vision system) or effectors (e.g. part feeders)
  - The Controller

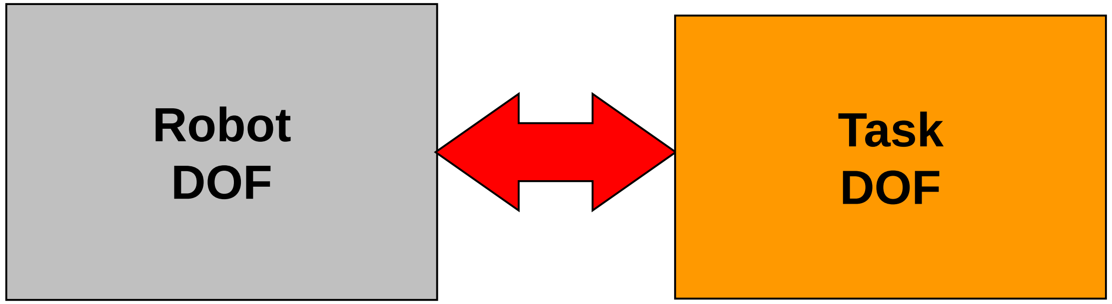
Manipulator Mechanical Design - Task Requirements



- **Task - Design Criteria**
  - Number of degrees of freedom
  - Workspace
  - Load capacity
  - Speed
  - Repeatability accuracy

Task Requirements - Number of DOF

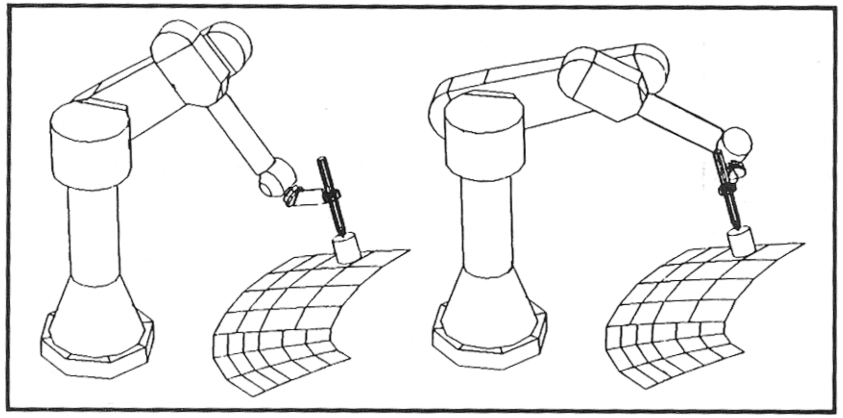
- The number of DOF in a manipulator should match the number of DOF required by the task.

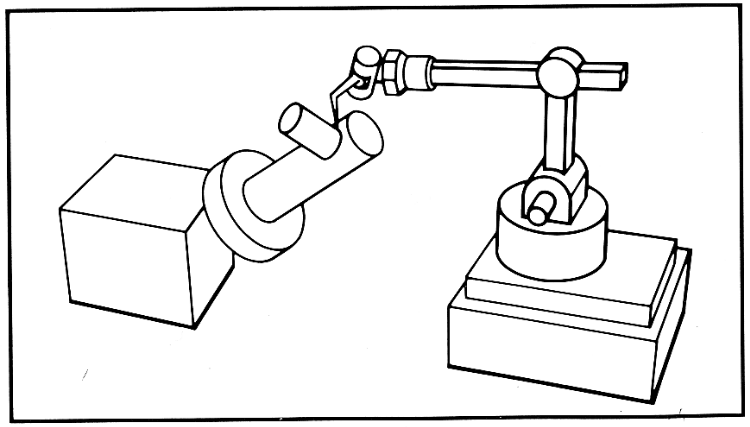


Task Requirements

- **Not all the tasks required 6 DOF for example:**
  - End effector with an axis of symmetry - Orientation around the axis of symmetry is a free variable,
  - Placing of components on a circuit board - 4 DOF (x, y, z, θ)

- **Dividing the total number of DOF between a robot and an active positioning platform**





PCB Assembly

Robotic Welding

Painting Robots

Task Requirements

- **Workspace (Work volume, Work envelope)**
  - Placing the target (object) in the work space of the manipulator
  - Singularities
  - Collisions
- **Load Capacity**
  - Size of the structural members
  - power transmission system
  - Actuators
- **Speed**
  - Robotic solution compete on economic solution
  - Process limitations - Painting, Welding
  - Maximum end effector speed versus cycle time
- **Repeatability & Accuracy**
  - Matching robot accuracy to the task (painting - spray spot 8 +/-2 “)
  - Accuracy function of design and manufacturing (Tolerances)

Kinematic Configuration

- **Joints & DOF** -
  - For a serial kinematic linkages, the number of joints equal the required number of DOF

- **Overall Structure**
  - Positioning structure (link twist 0 or +/- 90 Deg, 0 off sets)
  - Orientation structure

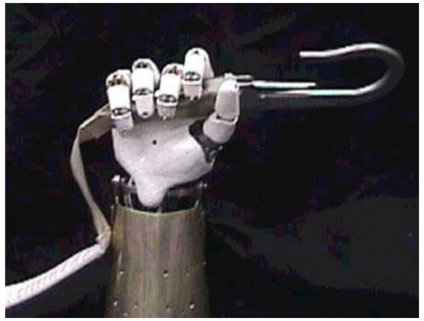
- **Wrist**
  - The last *n-3 joints orient the end effector*
  - *The rotation axes intersect at one point.*

Kinematic Configuration - Wrist

- **Joints**
  - Three (or two) joints with orthogonal axes
- **Workspace**
  - Theoretically - Any orientation could be achieved (Assuming no joint limits)
  - Practically - Severe joint angle limitations
- **Kinematics**
  - Closed form kinematic equations

End Effector (EE)

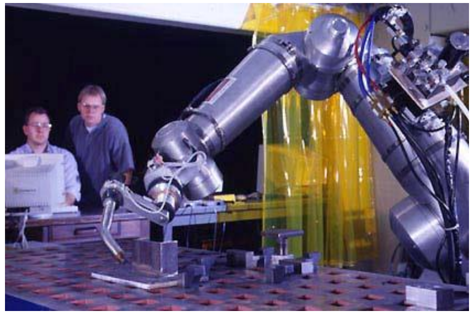
At the free end of the chain of links which make up the manipulator is the end effector. Depending on the intended application of the robot the end effector may be a gripper welding torch, electromagnet or other tool.



ROBONAUT - Hand (NASA)

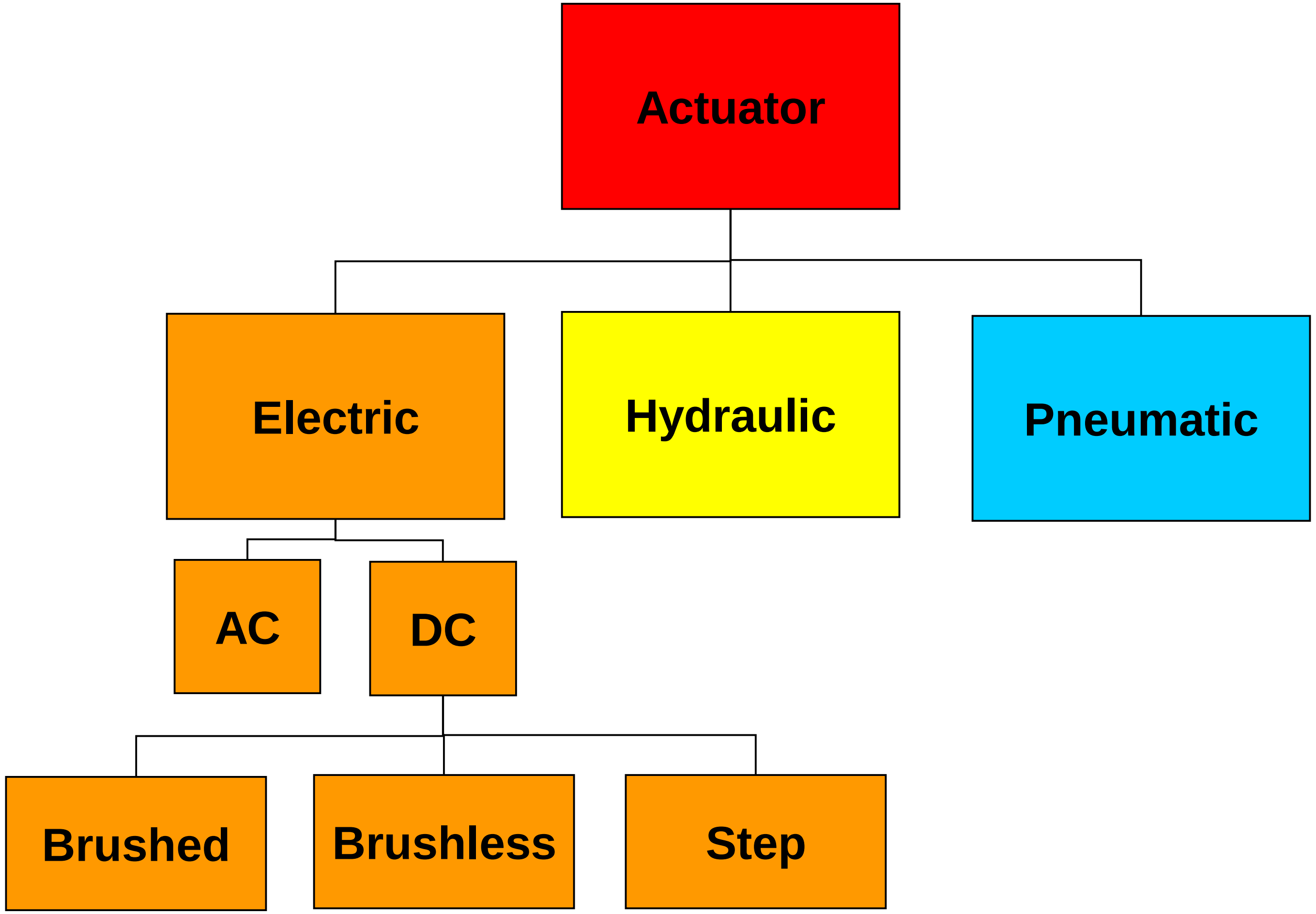
Stanford / JPL- Hand (Salsilbury)

Utha / MIT Hand

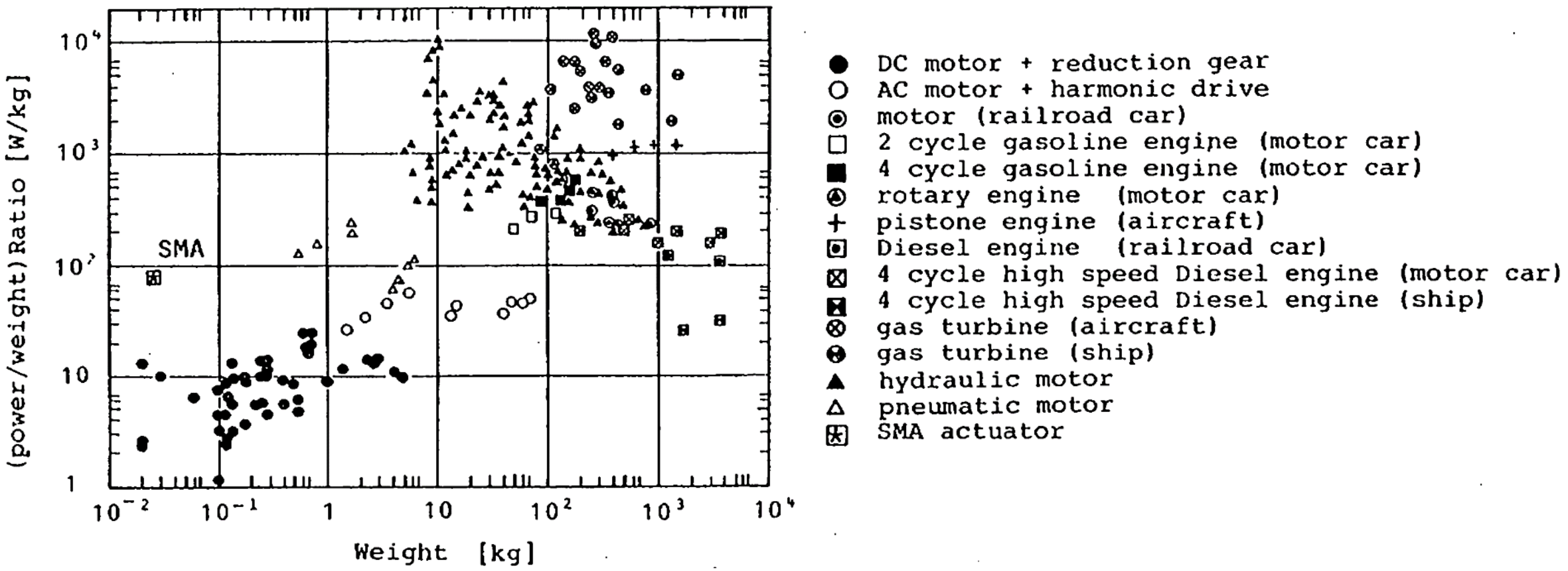


NIST - Advanced Welding Manufacturing System

Actuation

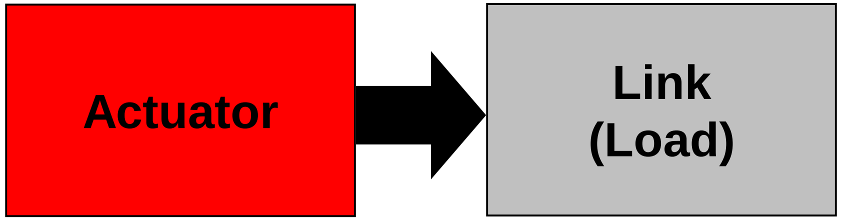

Actuator
Electric
Hydraulic
Pneumatic
AC
DC
Brushed
Brushless
Step

Actuation – Power to Weight Ratio

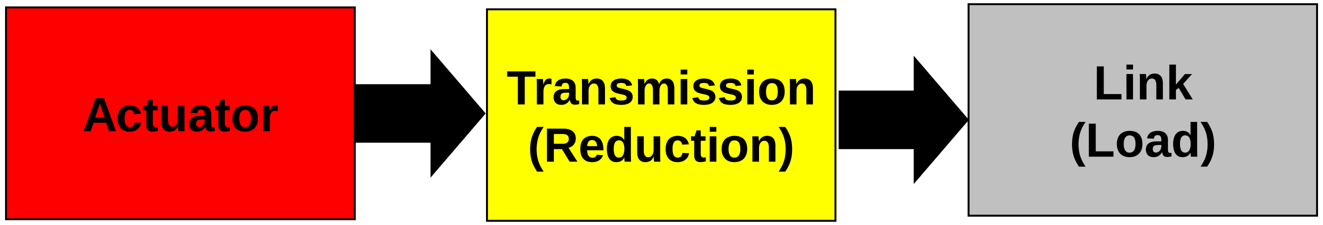


Actuation Schemes

- Direct Drive



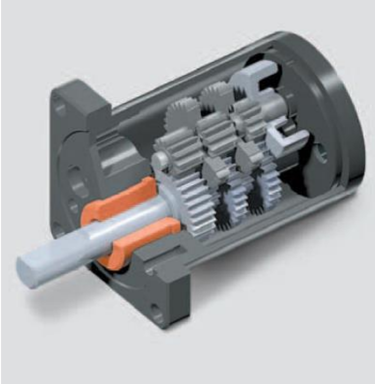
- Non Direct Drive

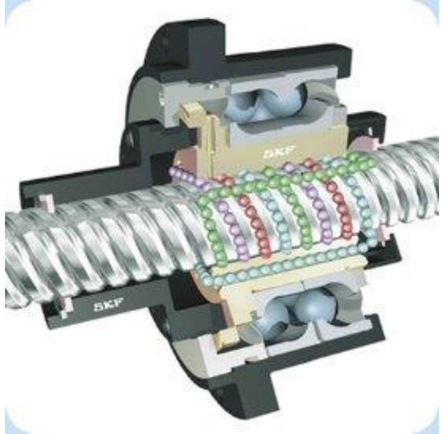


Reduction & Transmission Systems

Transmission

- Gears
- Cable
- Belt
- Chain
- Screw





Types of Gears

Super Gears

Helical Gears

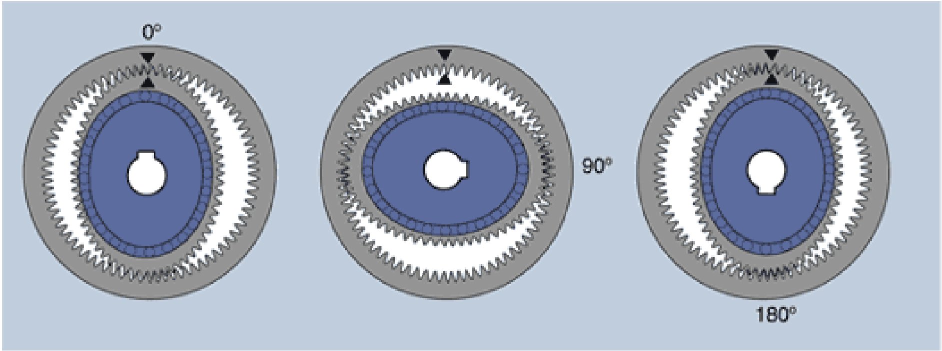
Rack & Pinion Gears

Bevel Gears

Hypoid Gears

Worm Gears

Gearbox / Gearhead



Harmonic Drive

Reduction & Transmission Systems

$$\mu \ P_{in} = P_{out}$$

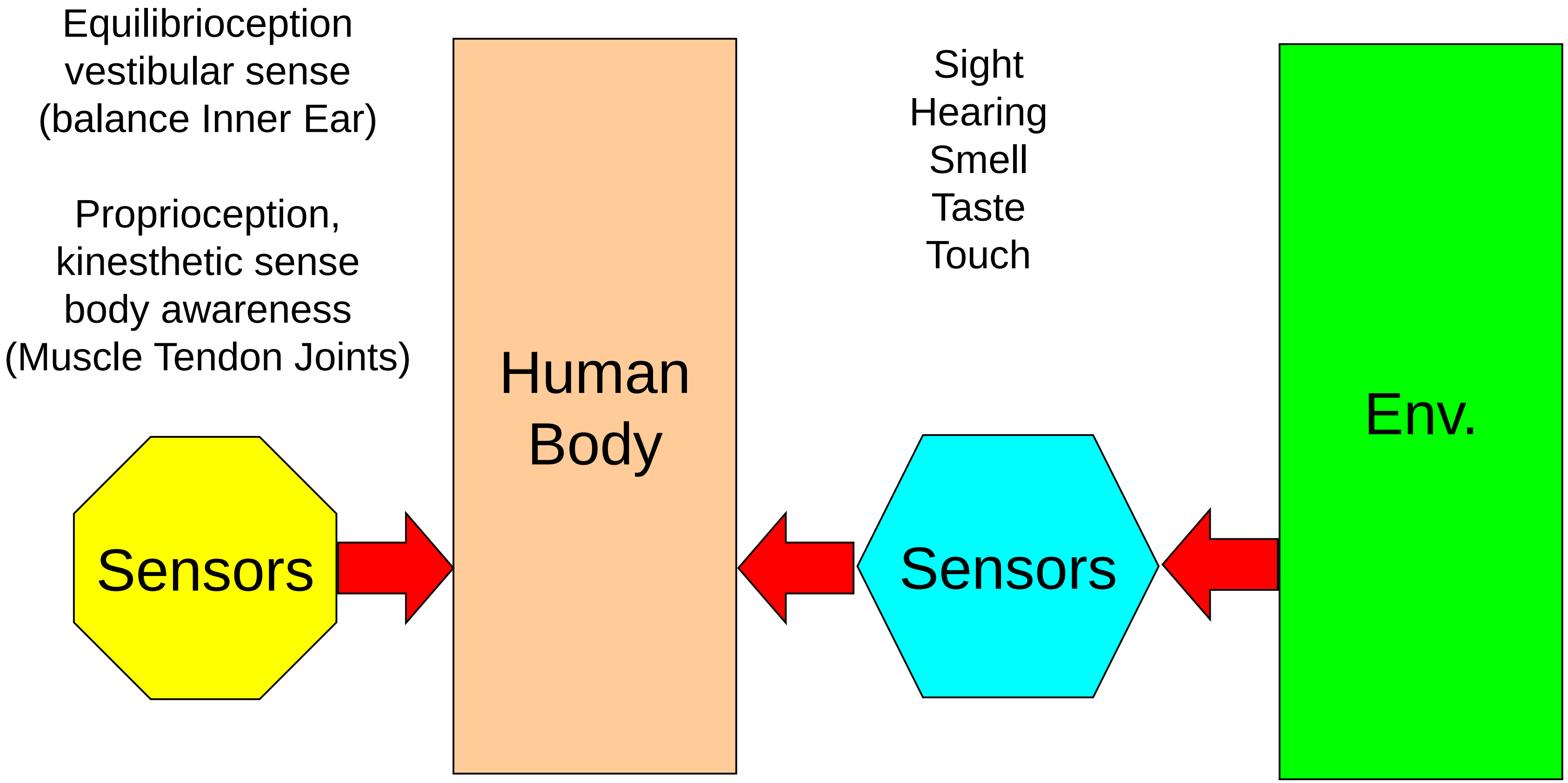
$$\mu \ T_{in}\omega_{in} = T_{out}\omega_{out}$$

$$\frac{T_{out}}{\mu \ T_{in}} = \frac{\omega_{in}}{\omega_{out}} = n \qquad (n > 1)$$

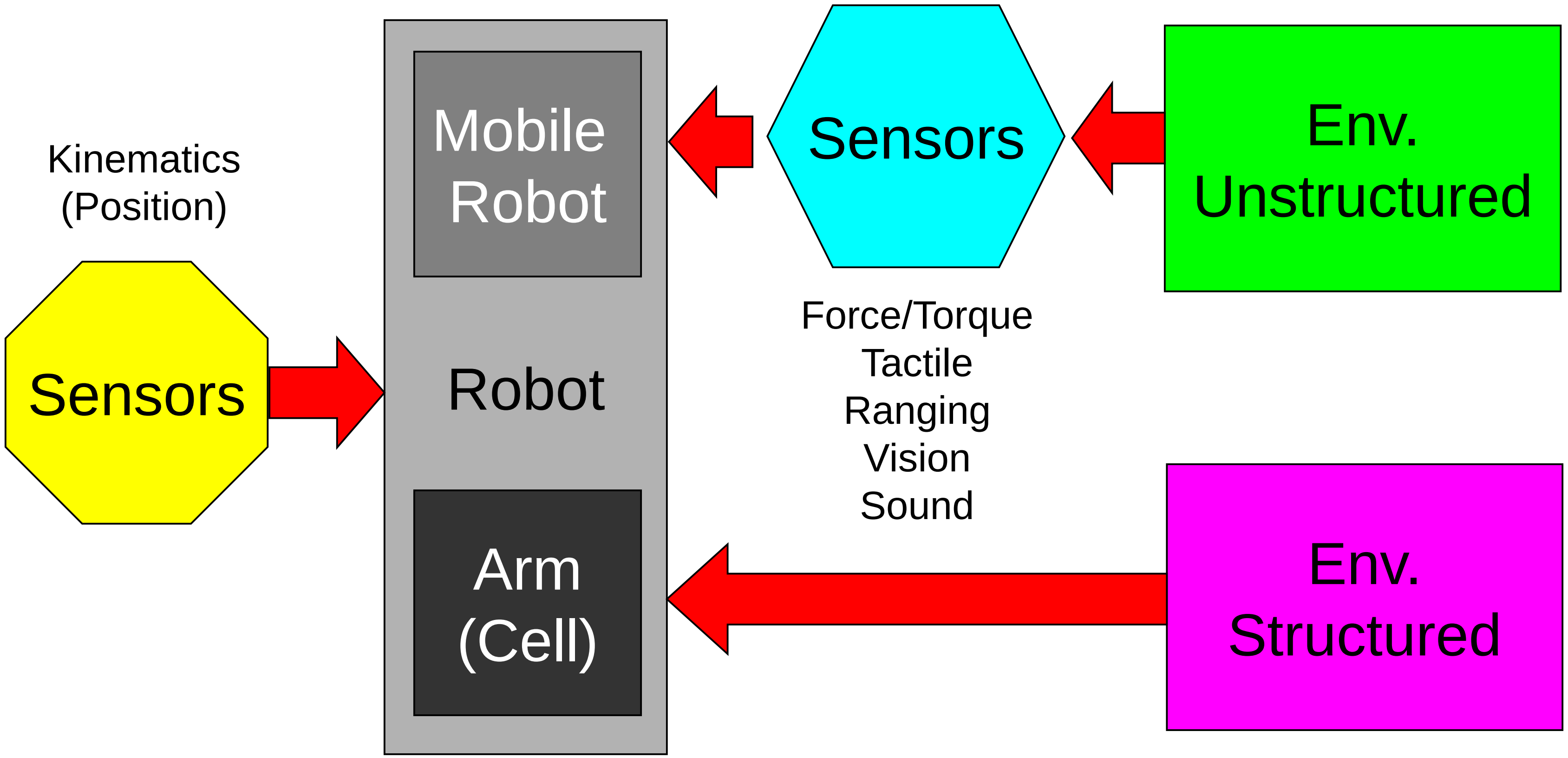
$$\mu \ \approx 0.5 - 0.9$$

Limiting Factors ω_{in}, T_{out}

Sensors – Human Body



Sensors – Robot



Manipulator Design

- Requirements
  - Task
  - Load
  - Time (speed / cycle-time)
  - Environment
  - Cost
- Design
  - No. of DOF
  - Workspace
  - Kinematics configuration
  - Dynamics properties
  - Actuation
  - Sensors
  - Accuracy
  - Reputability
- Analysis
  - Kinematics
  - Link length optimization
  - Singularities
  - Dynamics
  - Actuation optimization
  - Trajectory Analysis
  - Modal Analysis
  - Cost Analysis
  - Control
    - Low level (servo)
    - High level (sensor fusion)

Applications

Medical Robotics

Robotic Systems – Medical – Wearable Robot

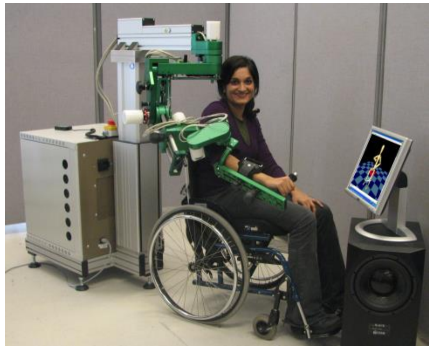
Exos

Exo-UL7
Bionics Lab - UCLA

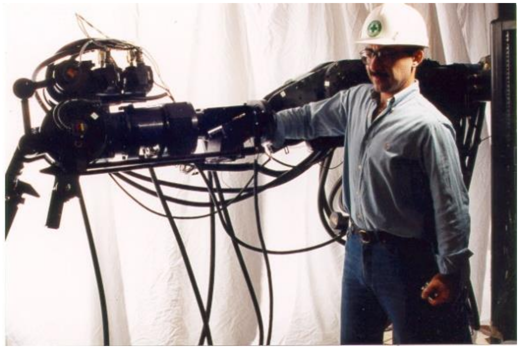
MGA
Maryland-Georgetown Army

Panasonic

Percro
University of Pisa - Italy



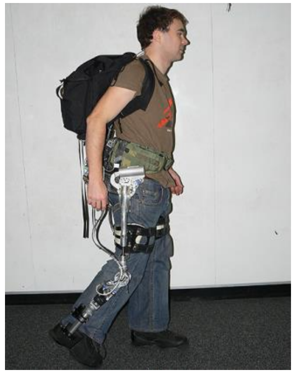
ARMin
Catholic University of America



Human Power Extender
UC Berkeley

Robotic Systems – Medical – Wearable Robot

HAL



MIT

BLEEX
Berkeley Robotics Lab - UCB

Video Hyperlink

Video Hyperlink

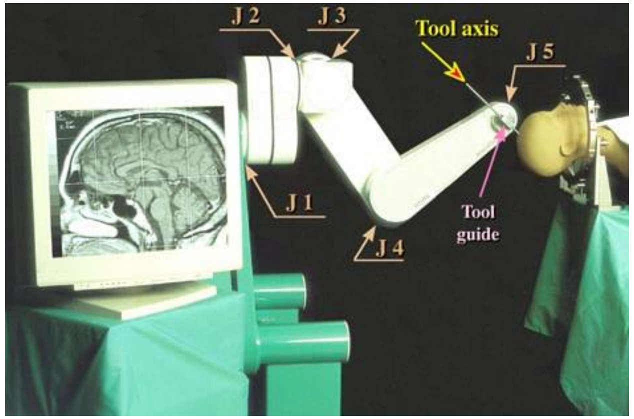
Video Hyperlink

Hardyman
GE 1965

Sarcos

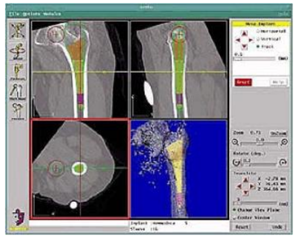
Video Hyperlink

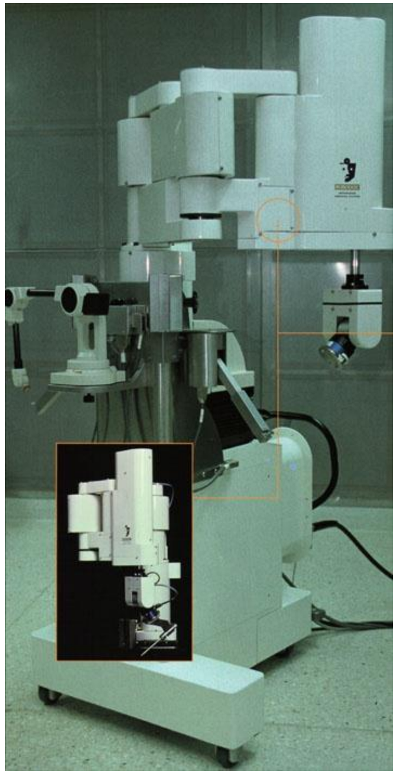
Robotic Systems – Medical – Surgical Robot



Neuromate

Integrated Surgical System (ISS)

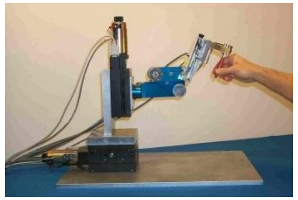




RoboDoc

Integrated Surgical System (ISS)

Robotic Systems – Medical – Surgical Robot

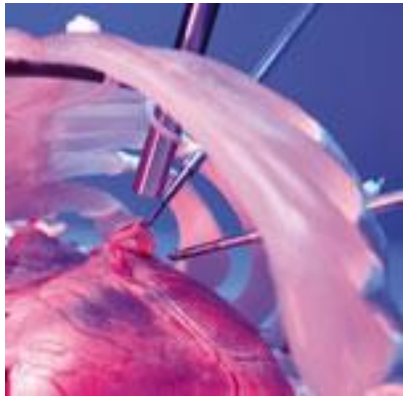
     

M7	*Zeus*	*DaVinci*		*Steady Hand*	*Raven*
SRI	*Computer Motion*	*Intuitive Surgical*	*UC Berkley*	*Hopkins*	*University of Washington*

Robotic Systems – Medical – Surgical Robot

AESOP
Computer Motion, Inc.
Goleta, CA



The AESOP Endoscope Positioner is a seven degree-of-freedom robotic arm, which mimics the form and function of a human arm to position an endoscope during minimally invasive surgery.

Using predefined voice commands, the surgeon is able to directly control a stable, responsive surgical image during long, complex procedures. The AESOP system provides a level of stability that is impossible to achieve with a human endoscope holder and frees up the medical professional for other patient- and surgeon-oriented duties.

www.computermotion.com

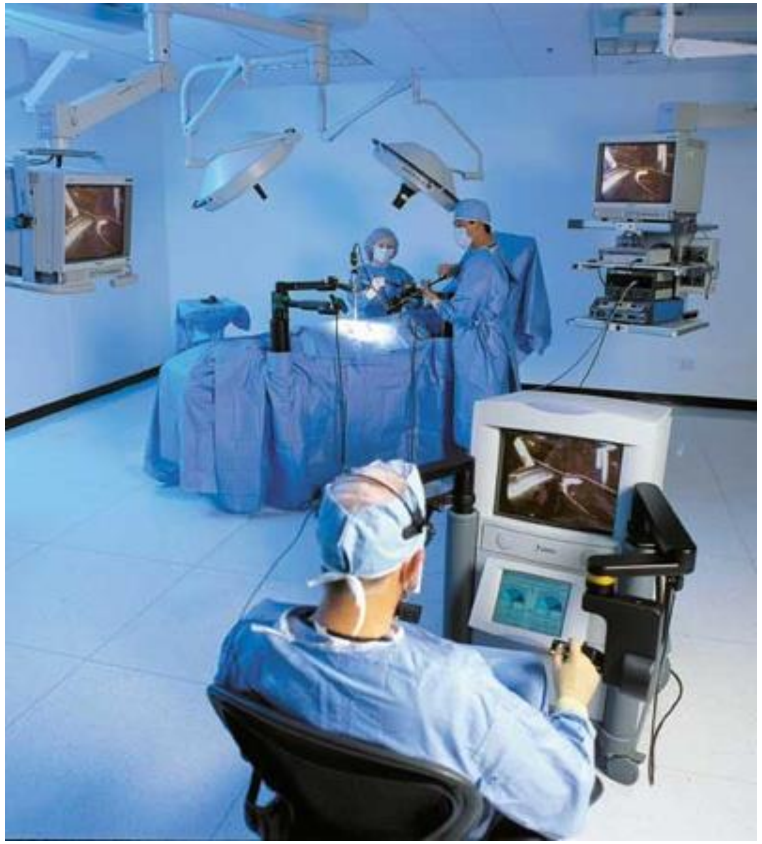
Robotic Systems – Medical – Surgical Robot

ZEUS

Computer Motion, Inc.

Goleta, CA

The ZEUS Robotic Surgical System is comprised of an ergonomic surgeon console and three table-mounted robotic arms, which act as the surgeon's hands and eyes during minimally invasive surgery. While sitting at the console, the surgeon controls the right and left robotic arms that translate to real-time manipulation of the surgical instruments within the patient's body. The third arm incorporates the AESOP technology, providing the surgeon with a controlled and steady view of the internal operative field.



www.computermotion.com

Robotic Systems – Medical – Surgical Robot

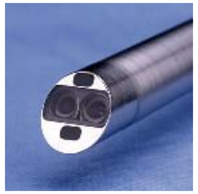
da Vinci

Intuitive Surgical, Inc.

Mountain View, CA

The da Vinci™ Surgical System consists of a surgeon's console, a patient-side cart, a high performance vision system and our proprietary instruments. Using the da Vinci Surgical System, the surgeon operates while seated comfortably at a console viewing a 3-D image of the surgical field. The surgeon's fingers grasp the instrument controls below the display with wrists naturally positioned relative to his or her eyes. Our technology seamlessly translates the surgeon's movements into precise, real-time movements of our surgical instruments inside the patient.

www.intuitivesurgical.com



Robotic Systems – Medical – Surgical Robot

Integrated Surgical Systems, Inc.
Davis, CA

ROBODOC

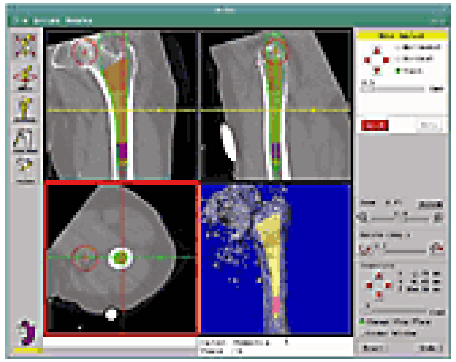
Total hip replacement- The robot mills a cavity in the femur for a prosthetic implant. The system is designed to accurately shape the cavity for a precise fit with the implant.

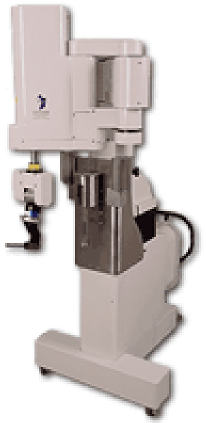
Total knee replacement - The robot planes knee surfaces on the femur and tibia to achieve a precise fit for the implant.

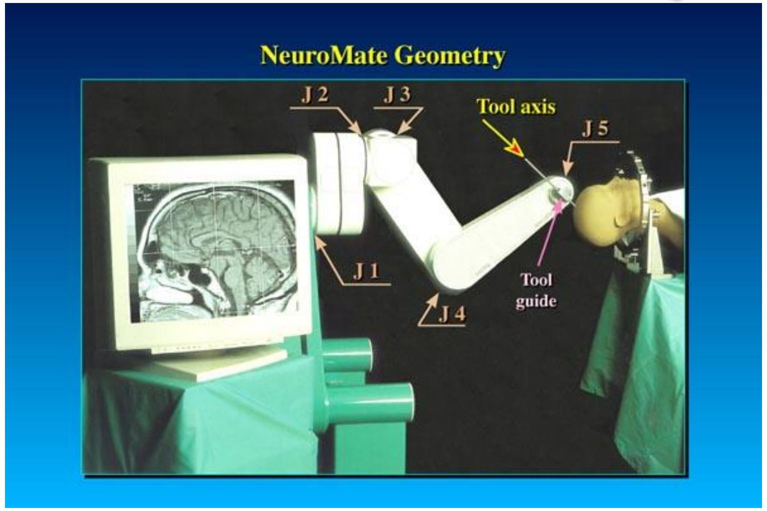
NeuroMate is a computer-controlled, image-directed robotic system for stereotactic functional brain surgeries. The Frameless NueroMate System eliminates the need to use the cumbersome and very painful frames that are traditionally used for many brain surgeries.

The system orients and positions a variety of surgical tools.

www.robodoc.com





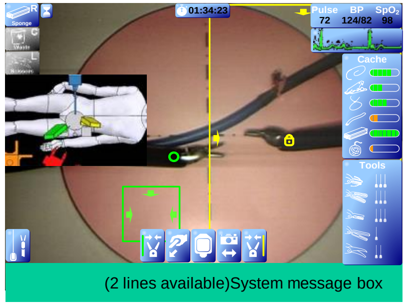


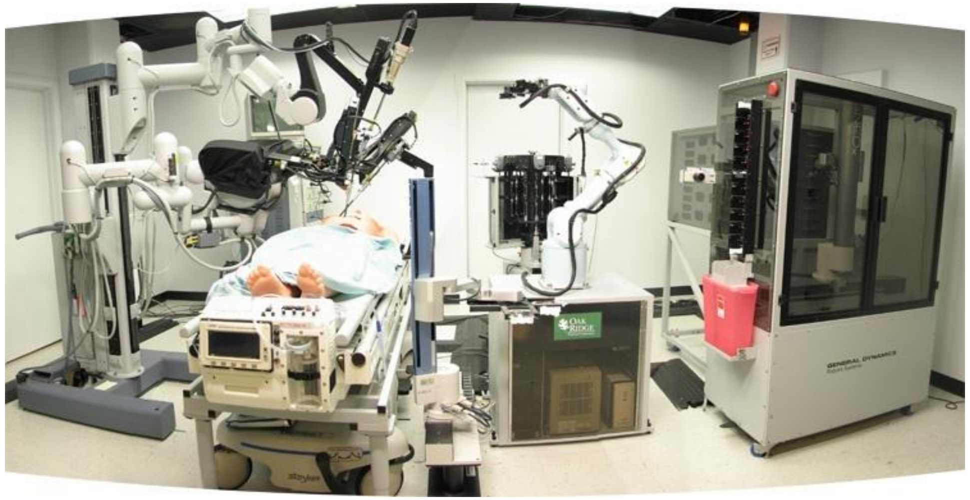
Robotic Systems – Medical – Surgical Robot

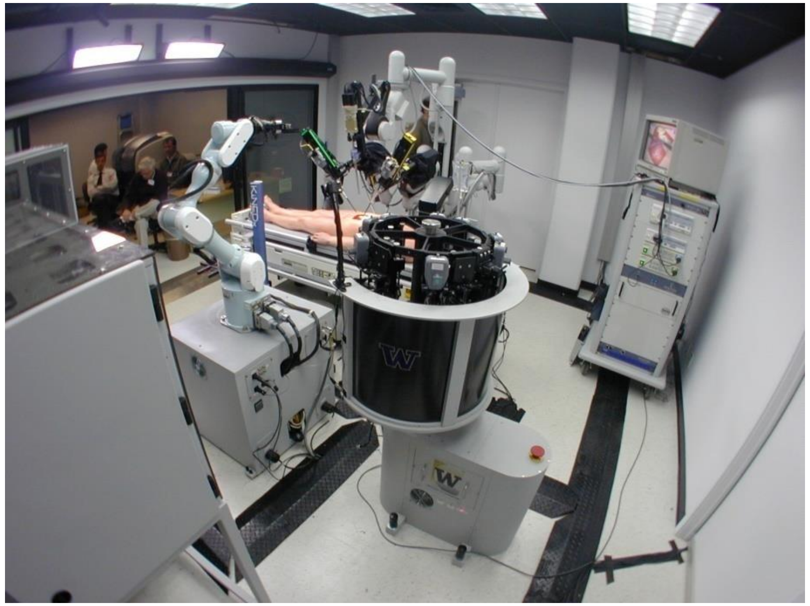
Raven I – Surgical Robot

Robotic Systems – Medical – Surgical Robot

Trauma Pod (SRI)







Trauma Pod Phase I – DARPA Project – Demo

Applications

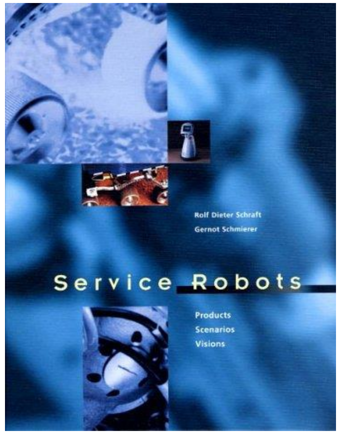
General

Robotic Systems - References

Service Robots

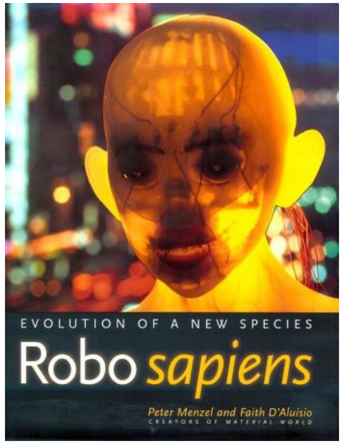
by G. Schmierer, and R.F. Schraft

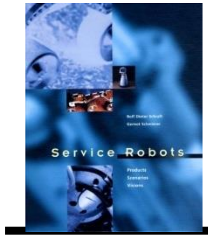
http://www.ipa.fhg.de/srdatabase



Robo Sapiens

by P. Menzel (Photographer),
F. D’Aluisio, C.C. Mann (Editor)
http://robosapiens.mit.edu/





Robotic Systems - Agriculture and Forestry

Walking Forestry Manipulator

Plustech Oy Finland

Innovative technology is used among agriculture and forestry in order to increase the work´s efficiency. The Finnish company Plustech Oy has developed the world´s first walking forestry manipulator whose ingenious walking kinematics were copied from examples that Mother Nature provides. The computer-controlled, ***six-legged walking mechanism*** suits any of the various kinds of ground conditions that may be found in forests around the world. Yet it is designed not to harm the environment it is working in, e.g. its weight is at all times evenly distributed on the forest floor, and it prevents soil erosion. The device is controlled by a ***joystick*** and its claw is used to handle and move tree trunks.

Video Hyperlink

Robotic Systems – Legged Locomotion

Little Dog
Boston Dynamics

Video Hyperlink

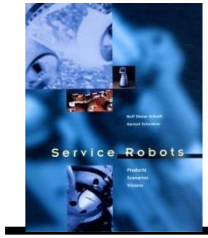
Big Dog
Boston Dynamics

Video Hyperlink

Video Hyperlink (j)

Video Hyperlink

Video Hyperlink



Robotic Systems - Care / Rehabilitation

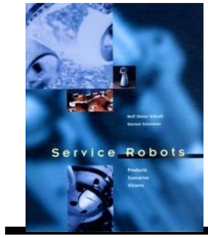
FRIEND - Functional Robot Arm with User Friendly Interface for Disabled People

University of Bremen

Germany

The aim of FRIEND is the development of a robot system which supports people with severe physical impairment in daily life and in the work environment. The system consists of an electric powered wheelchair, a MANUS robot arm and a standard PC which is attached in a rugged case to the back side of the wheelchair. A tray and a flat screen are mounted at the left side of the wheelchair. The structure of the entire control system is coarsely divided up into the components robot controller, command interpreter, administration module for pre-programmed motions and man-machine interface. The user-oriented man-machine interface can be operated in two different modes: pre-programmed motions and user-controlled robot movements.

Video Hyperlink



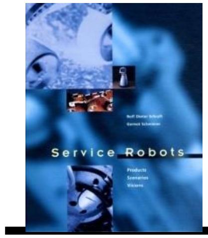
Robotic Systems - Construction

The Road Robot

ESPRIT program European Union

The Road Robot is self-navigating, self-steering and completely computerized road finisher. The goal was for road engineers to build road surfaces more rationally, more environmentally-friendly. The entire process consists of four subsystems, yet each one has its own module: the logistics of coated materials, the traveling mechanism, the geometry of the road surface and the plank. There are two different ways of operating the device: either by radio from the engineers´ office or with the on-board computer touch screen. The Road Robot´s diesel-electric drive decreases the noise up to 12 dB (A), produces 50% less exhaust fumes and requires 50% less gasoline than a conventional road finisher of an equal performance level.

Video Hyperlink

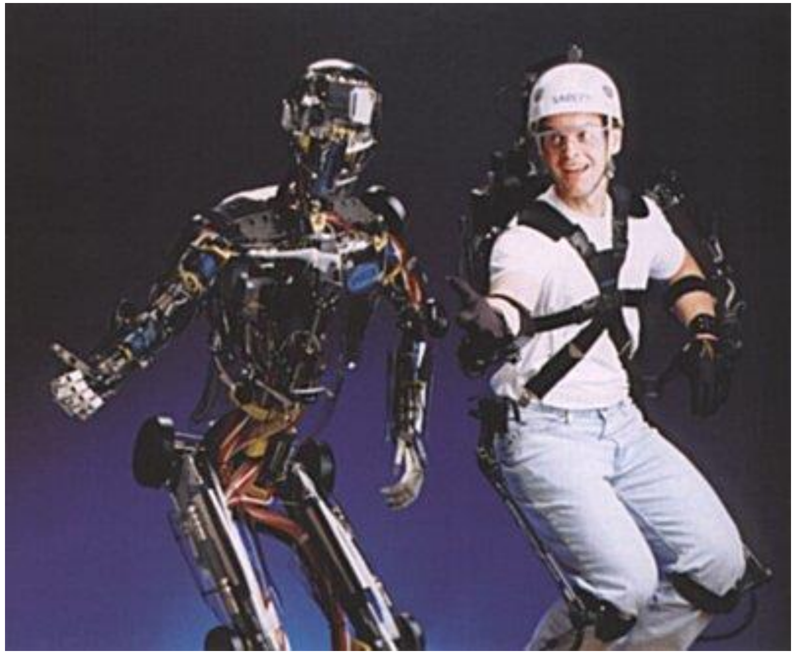


Robotic Systems - Master / Slave Teleoperator

Master / Slave Robot

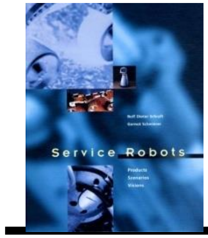
Sarcos

Puppeteers in the entertainment business, turn master-slave robots into interactive actors that react in real-time. Controlling an anthropomorphic robot requires only one person to operate, even though these man-like robots may possess up to ***56 degrees of freedom*** which may all have to be directed simultaneously. An Exoskeleton equipped with position sensors registers the master´s movements and transfer them to the robot´s control system. The control algorithms ensure similar movements of the robot.



www.sarcos.com

Video Hyperlink



Robotic Systems - Hazardous Duties

Telerob

Ostfildern, Germany

- Fire Fighting
- Nuclear Reactor
- Explosives

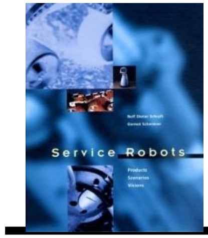
http://www.telerob.com

iRobot

Snake Robot

iRobot & Arm

iRobot Military



Robotic Systems - Recreation

Intelecady

GolfPro International

Santa Clara, CA

The Intelecady is a computer-generated, electrically powered golf caddie robot. It navigates around the golf course with its telecommunications skills and sensors. A small coded transmitter, attached to the golfer, is used to follow its „master". A digital map of the golf course is memorized on the on-board computer. Zones where the caddie is not supposed to be are specifically marked on the map. The device stops right before steep inclines or downward slopes and it´s not until the golfer leaves this area that the Intelecady starts following him again. The balls are located with the halp of GPS. Ultrasound sensors detect any kind of obstacles that may be in the robot´s way.

Shadow Caddy